A Hydrostratigraphic Model for the Shallow Aquifer Systems of the Gambier Basin and South Western Murray Basin

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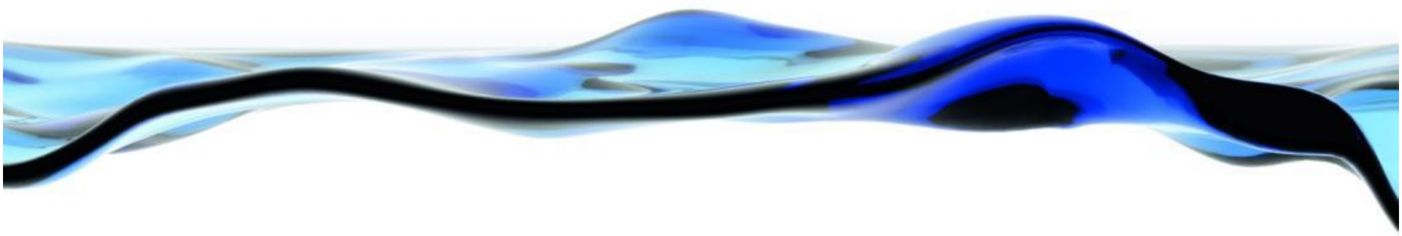

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Preface

South East Regional Water Balance Project Background

The South East Regional Water Balance project is a collaboration between Flinders University, CSIRO and the Department of Environment, Water and Natural Resources (DEWNR), funded by the Goyder Institute for Water Research. The project commenced in September 2012, with the objective of developing a regional water balance model for the Lower Limestone Coast Prescribed Wells Area (LLC PWA). The project was initiated following conclusions from the South East Water Science Review (2011) that, due to a number of gaps in understanding of processes that affect the regional water balance, there is uncertainty about the amount of water that can be extracted sustainably from the Lower Limestone Coast region as a whole. The review also concluded that, because of the close link between groundwater and surface water resources in the region, surface water resources and ecosystems are particularly vulnerable to groundwater exploitation.

The South East Regional Water Balance project follows on from the report of Harrington et al. (2011), which recommended that a consistent framework of models is required to support water management in the South East, with the first step being a regional groundwater flow model to:

- bring together all existing knowledge,
- address regional scale water balance questions
- provide boundary conditions for smaller scale models to address local scale questions, including those around "hotspot" areas and significant wetlands.

Harrington et al. (2011) also identified the critical knowledge gaps that limit the outcomes from a regional scale model. These included but were not limited to:

- Spatial and temporal variability in groundwater recharge and evapotranspiration.
- Interaquifer leakage and the influence of faults on groundwater flow.
- The nature of wetland-groundwater interactions
- Understanding of processes occurring at the coastal boundary
- Surface water-groundwater interactions around the man-made drainage network
- The absence of information on historical land use and groundwater extraction

The South East Regional Water Balance project has included numerous tasks that have sought to improve the conceptualisation of the regional water balance, address some of the critical knowledge gaps, incorporate this and existing information into a regional groundwater flow model and understand how this improved understanding can be used in the management of wetland water levels.

An overview of the project and its output can be found in Harrington et al. 2015. *South East Regional Water Balance Project – Phase 2. Project Summary Report.* Goyder Institute Report 15/39.

Executive Summary

A three-dimensional hydrostratigraphic model of the entire regional groundwater flow system that includes the Gambier Basin and the south western Murray Basin has been produced. The domain of this model stretches from the Dundas Plateau in Victoria to the Padthaway Ridge in South Australia and includes the Lower Limestone Coast and Padthaway Prescribed Wells Areas in South Australia, as well as part of the Border Designated Area (Zones 1A/1B to 6A/B and part of Zones 7A/B). The domain of the hydrostratigraphic model was governed by the boundaries of the South East Regional Water Balance Model, which is being developed as part of a Goyder Institute for Water Research project. This groundwater flow model required a hydrostratigraphic model that covered the whole regional groundwater flow system that encompasses the Lower Limestone Coast Prescribed Wells Area. This is the first cross-border hydrostratigraphic model to be produced for this region.

The hydrostratigraphic model includes five layers, Layer 1: the Quaternary Limestone Aquifer, Layer 2: the Upper Mid-Tertiary Aquifer (Gambier / Murray Group Limestone Aquifer), Layer 3: the Upper Tertiary Aquitard, Layer 4: The Lower Tertiary Aquifer (Mepunga Formation) and the Lower Tertiary Confined Aquifer (Dilwyn Sand / Renmark Group Aquifer) and Layer 5: the Pre-Cainozoic Sediments and Basement (however, the model does not include data for the base of Layer 5).

The model includes the following datasets:

Topographic Surface

- SA/VIC State 1 second Digital Elevation Model (DEM), later updated with a version that includes lidar DEM data where available.

Top of Layer 2 (Top of Gambier / Murray Group Limestone)

- 2,697 stratigraphic data points for the South Australian portion of the model domain.
- 209 stratigraphic data points for the Victorian portion of the model domain

Top of Layer 3 (Top of Aquitard)

- 733 data points for the whole model domain, including Victoria.

Top of Layer 4 (Top of Dilwyn Sand / Renmark Group) – Layer 4 includes the Pember Mudstone and Pebble Point Formation.

- 874 stratigraphic data points for the South Australian portion of the model domain.
- 83 stratigraphic data points for the Victorian portion of the model domain

Top of Layer 5 (Top of Basement)

- 243 points for the South Australian portion of the study area. These were restricted to the Murray Basin (northern) portion of the study area.
- Contours of basement outcrops in the northern part of the SA portion of the study area.
- Contours derived from petroleum well and seismic data for the southern portion of the South Australian part of the study area.
- 63 points on the Victorian portion of the study area.

The hydrostratigraphic model was created in an ArcGIS framework and is available as an ArcGIS geodatabase. The parent datasets described above are also available in ArcGIS format.

After a preliminary model was produced, the resulting layer thicknesses were first checked by local expert hydrogeologists to ensure that they were consistent with their understanding of the aquifer system. This resulted in some adjustments being made and some additional data being added to the model, after which the model was further tested, in particular by comparing the base of the unconfined aquifer with the

September 2011 water table contours, to identify any areas where the unconfined aquifer is potentially dry and to compare with maps of surface water bodies for the region. Development and calibration of a regional groundwater flow model using the hydrostratigraphic model is underway and may further add to the understanding of the accuracy of the hydrostratigraphic model.

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This work was carried out in partnership by the South Australian Department of Environment, Water and Natural Resources (DEWNR) and the National Centre for Groundwater Research and Training (NCGRT) at Flinders University. The NCGRT is an Australian Government initiative, supported by the Australian Research Council and the National Water Commission. The work was partly funded by the Goyder Institute for Water Research under the South East Regional Water Balance project.

1 Introduction

1.1 Background

A conceptual hydrostratigraphic framework for the South East region of South Australia was compiled as part of the South East National Water Initiative (NWI) project, and a three-dimensional model constructed from this (Lawson et al., 2009). The model included stratigraphic logs from a combination of groundwater observation wells, water supply and irrigation bores and petroleum exploration holes, which were available from the state drillhole database, SAGeodata, or as microfiche records held by the South Australian Department of Environment, Water and Natural Resources (DEWNR) (then the Department for Water – DFW). Additional investigation holes that had been recently drilled were also included. Overall, the model included data from 327 well logs, including 5 newly drilled wells in the Victorian Border Zone 3B.

Subsequent to this, the hydrostratigraphic model for the whole South East region of SA (including the Gambier Basin and the south-western portion of the Murray Basin) was revised by DEWNR for the Bureau of Meteorology National Aquifer Framework project. This new model incorporated additional stratigraphic interpretation, particularly for the Murray Basin portion of the study area. At the same time, the Goyder Institute South East Regional Water Balance project required a hydrostratigraphic model for an area that included the domain of the revised hydrostratigraphic model but also extended across the SA/Victorian border. This model domain was governed by natural groundwater flow patterns and therefore extended across the border to the Dundas Plateau, considered to be a natural hydraulic boundary for groundwater flow in the Tertiary aquifers. For this reason, it was decided to extend the hydrostratigraphic model already being developed by DEWNR to cover the whole domain of the regional groundwater flow model. As mentioned above, the existing hydrostratigraphic model included only 5 data points from the Victorian side of the Border. Additional hydrostratigraphic data from Victoria was obtained from the Victorian DSE and, although the interpretations and unit descriptions were slightly different, there was a good spatial coverage of data in the study area and this data could be interpreted to extend the South Australian hydrostratigraphic model to cover the whole study area.

The final hydrostratigraphic model product is available in a raster format in an ArcGIS framework, with the parent datasets also available in ArcGIS formats. Although the model was developed to support the construction of the regional groundwater flow model for the Goyder Institute's South East Regional Water Balance (SERWB) project, this stand-alone report has been prepared as documentation to accompany the hydrostratigraphic model files when they are to be used for other purposes. The report is intended to accompany the hydrostratigraphic model and, as such, the figures in this report are for illustrative purposes only, with the detail that can be presented in figures in a report recognised as being extremely limited. Development of the hydrostratigraphic model in collaboration with the South East Regional Water Balance project has allowed the model to be rigorously tested within the framework of a regional groundwater flow model.

1.2 Associated Reports and Research Papers

The following reports and research papers are also associated with the South East Regional Water Balance project:

Technical Reports:

Harrington, N and Lamontagne, S (eds.), 2013*, Framework for a Regional Water Balance Model for the South Australian Limestone Coast Region.* Goyder Institute for Water Research Technical Report 13/14.

Morgan, LK, Harrington, N, Werner, AD, Hutson, JL, Woods, J and Knowling, M, 2015, *South East Regional Water Balance Project – Phase 2. Development of a Regional Groundwater Flow Model.* Goyder Institute for Water Research Technical Report 15/38.

Doble, R, Pickett, T, Crosbie, R, Morgan, L, 2015, *A new approach for modelling groundwater recharge in the South East of South Australia using MODFLOW,* Goyder Institute for Water Research Technical Report 15/26.

Taylor, AR, Lamontagne S, Turnadge, C, Smith, SD and Davies, P, 2015, *Groundwater-surface water interactions at Bool Lagoon, Lake Robe and Deadmans Swamp (Limestone Coast, SA): Data review.* Goyder Institute for Water Research Technical Report 15/13.

Smith, SD, Lamontagne, S, Taylor, AR and Cook, PG, 2015, *Evaluation of groundwater-surface water interactions at Bool Lagoon and Lake Robe using environmental tracers.* Goyder Institute for Water Research Technical Report 15/14.

Turnadge, CJ and Lamontagne, S, 2015, *A MODFLOW–based approach to simulating wetland–groundwater interactions in the Lower Limestone Coast Prescribed Wells Area*. Goyder Institute for Water Research Technical Report 15/12.

Barnett, S, Lawson, J, Li, C, Morgan, L, Wright, S, Skewes, M, Harrington, N, Woods, J, Werner, A and Plush, B, 2015, *A Hydrostratigraphic Model for the Shallow Aquifer Systems of the Gambier Basin and South Western Murray Basin*. Goyder Institute for Water Research Technical Report 15/15.

Harrington, N and Li, C, 2015, *Development of a Groundwater Extraction Dataset for the South East of South Australia: 1970-2013.* Goyder Institute for Water Research Technical Report 15/17.

Harrington, N, Millington, A, Sodahlan, ME and Phillips, D, 2015, *Development of Preliminary 1969 and 1983 Land Use Maps for the South East of SA*. Goyder Institute for Water Research Technical Report 15/16.

Harrington, N, Lamontagne, S, Crosbie, R, Morgan, LK and Doble, R, 2015, *South East Regional Water Balance Project: Project Summary Report.* Goyder Institute for Water Research Technical Report 15/39.

Research Papers:

Crosbie RS, Davies P, Harrington N and Lamontagne S (2015) *Ground truthing groundwater-recharge estimates derived from remotely sensed evapotranspiration: a case in South Australia.* Hydrogeology Journal 23(2), 335-350.

Lamontagne S, Taylor A, Herpich D and Hancock G (2015) *Submarine groundwater discharge from the South Australian Limestone Coast region estimated using radium and salinity.* Journal of Environmental Radioactivity 140, 30-41.

2 Overview of the study area

The area of interest for the South East Regional Water Balance project, which was the basis for determining the domain of the hydrostratigraphic model, is the Lower Limestone Coast Prescribed Wells Area (LLC PWA). However, the model domain is broader than this in order to capture the entire regional groundwater flow system. It is roughly bounded by the structural highs of the Padthaway Ridge and the Dundas Plateau and extends northward towards Keith (Figure 1). Hydrogeologically, it includes the Gambier Basin and the south-western margins of the Murray Basin. The following provides a broad overview of the characteristics of the South East region as an introduction.

2.1 Topography and Climate

The study area comprises an undulating coastal plain which generally slopes to the west and south-west toward the Southern Ocean (Figure 1). Topographic relief in the study area is generally low, rising to a maximum of 50 mAHD (metres above Australian Height Datum) along a series of north-west to south-east trending stranded coastal ridges. Topographic lows (i.e. < 30 mAHD) occur in inter-dunal regions. The highest points in the landscape are the Mount Gambier and Mount Schank volcanic cones, rising to 190 m and 120 mAHD respectively (Figure 1). Other, but less significant topographic highs in the study area include the Mount Burr and Naracoorte Ranges.

The climate in the South East region is Mediterranean, with hot dry summers and cool wet winters. Daily maxima range up to 40 °C in the summer months and as low as 10 to 12 °C during the winter months. A north-south rainfall gradient exists, with generally higher rainfall (approximately 800 mm/yr) occurring in the southern part of the region and lower rainfall (approximately 450 mm/yr) occurring further north. Approximately 75% of annual rainfall falls between April and October, which is typically when groundwater recharge occurs (i.e. when precipitation exceeds evapotranspiration). An approximate north-south evapotranspiration gradient also exists, with potential evapotranspiration ranging from approximately 1,400 mm/year in Mount Gambier to approximately 1700 mm/year in Keith, which is just north of the study area.

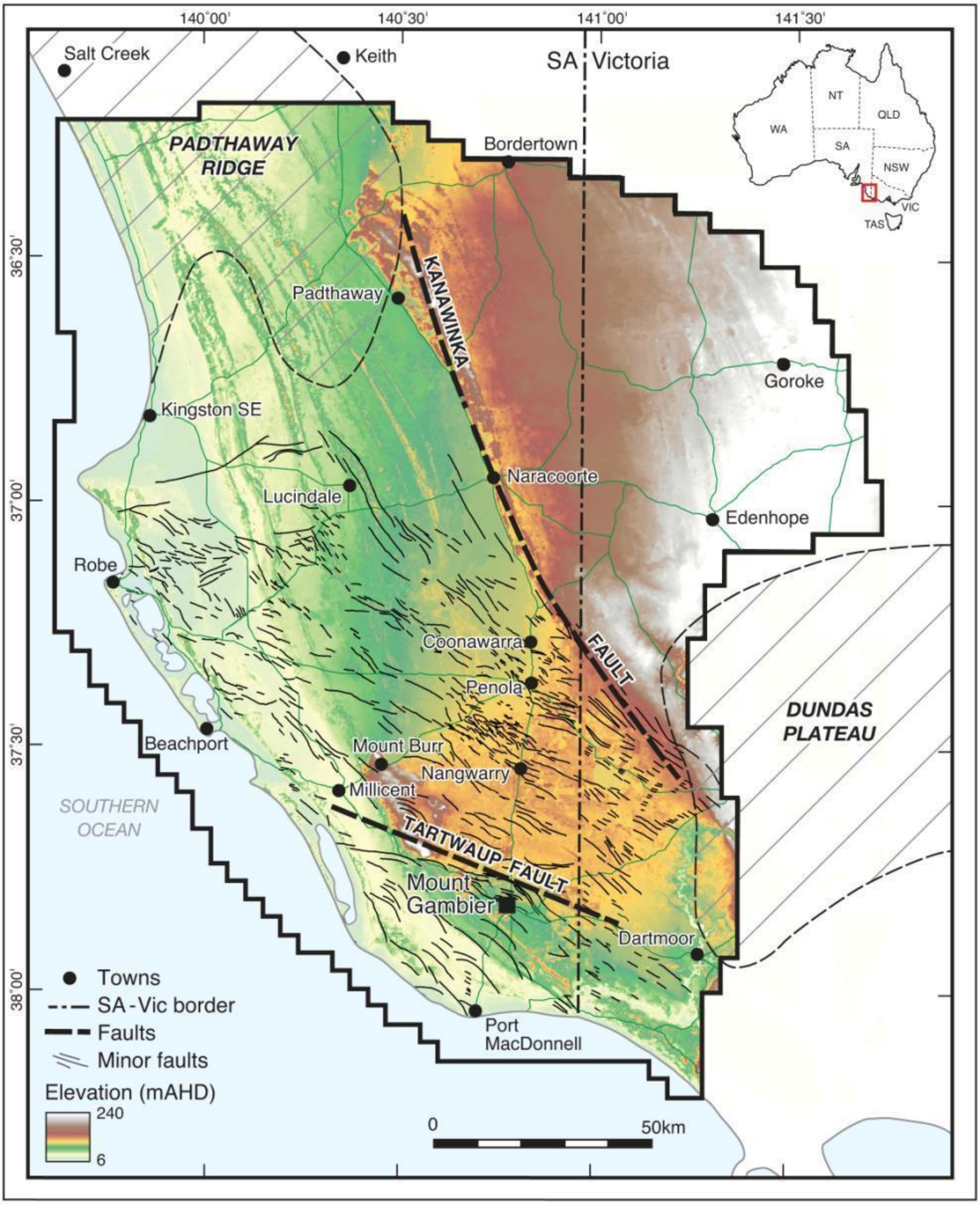


Figure 1 Location of study area for the SERWB project and therefore the hydrostratigraphic model (bounded by solid black line), showing topography, the Padthaway Ridge and Dundas Plateau structural highs and geologic faults.[1]

[1] Note: faults have only been mapped for the Otway Basin portion of the study area. The boundary between the Murray and Otway basins was recently re-interpreted to lie along a line approximately from Kingston to Lucindale, then south of Naracoorte along the Kanawinka Fault (Lawson et al., 2009).

2.2 Geological setting

The study area consists of the Gambier Basin, which is a Tertiary groundwater basin overlying the Western Otway Basin, and part of the south-western Murray Basin (Figure 1).

2.2.1 GAMBIER BASIN

The Otway Basin is an east-west elongate basin of approximately 100,000 km^2 containing a thick accumulation of mixed marine and terrestrial sediments deposited during the Cretaceous Period (Figure 2)(Smith et al., 1995). The Gambier Basin represents the most westerly of a series of groundwater basins overlying the Otway Basin, synonymous with the 'Gambier Embayment of the Otway Basin' (Smith et al, 1995). It is separated from the Murray Basin to the north by the Padthaway Ridge, a granitic basement high and by the Kanawinka Monocline to the north-east (Cobb and Barnett, 1994). It is bounded in the east by the Dundas Plateau (Love et al., 1993), where the water table lies within the pre-Cainozoic bedrock (Mann et al., 1994). In the south-east, it is separated from the neighbouring Tyrendarra Embayment of the Otway Basin by the Lake Condah High (Ryan et al., 1995; SKM, 2009). The basin extends offshore (Ryan et al., 1995).

A number of prominent structural features within the Gambier Basin are believed to exert significant influence on regional groundwater flow. In particular, the north-west trending Kanawinka Fault occurs in the north-east of the Basin and the west to north-west trending Tartwaup Fault occurs in the south of the basin (Figure 1). Both faults feature throws towards the south-west, with the magnitude of stratigraphic offset diminishing toward the surface. The Tartwaup Fault forms part of a major structural hinge line, with Cretaceous and Tertiary sediments rapidly increasing in thickness to the south (Gravestock et al., 1986). A number of smaller parallel faults are associated with the Tartwaup Fault (Figure 1) (Lawson et al., 2009). An important structural high, the Gambier Axis (Kenley, 1971) occurs to the north of the Tartwaup Fault. Recent mapping of fault locations in Tertiary sequences has revealed that the northern boundary of the Gambier Basin is likely to occur approximately along the Kingston-to-Naracoorte line, and is associated with a magnetic high located between Lucindale and Struan (Lawson et al., 2009). This can be approximated by following the northern extent of mapped minor faults in Figure 1.

Sedimentation in the Otway Basin commenced in the Early Cretaceous with deposition of shales, lacustrine volcanogenic sand and fluvial clays of the Otway Group. This was followed by the deposition of the claystone, mudstone, and sand of the Late Cretaceous Sherbrook Group. Sedimentation in the Tertiary Gambier Basin commenced in the Palaeocene to Early Eocene Wangerrip Group, containing the Pember Mudstone and the Dilwyn Formation. The latter unit includes the Tertiary Confined Sands Aquifer and the Dilwyn Clay aquitard. Increasing marine influence led to deposition of the Middle to Late Eocene marginal-marine Nirranda Group (including the Mepunga Formation and the Narrawaturk Marl). In the Late Eocene to Middle Miocene the marine Heytesbury Group comprising the Gambier Limestone which is currently part of the regional unconfined aquifer.

Since the Pleistocene the southern area of the Gambier Basin has been altered by volcanic activity, with the remnant volcanic cones of Mount Gambier, Mount Schank and Mount Burr now prominent topographic features in the landscape.

Eustatic sea level rise during the Pleistocene resulted in a number of marine transgressions that extended as far inland as the Kanawinka Fault and caused reworking of Tertiary sedimentary units that resulted in deposition of the Bridge water Formation comprising fossiliferous aoelian sediments that formed in strand lines sub-parallel to the coastline as the ocean regressed, with the shallow marine limestone of the Padthaway Formation being deposited in inter-dunal areas. These units, where present, overly the karstic Gambier Limestone and form part of the regional unconfined aquifer.

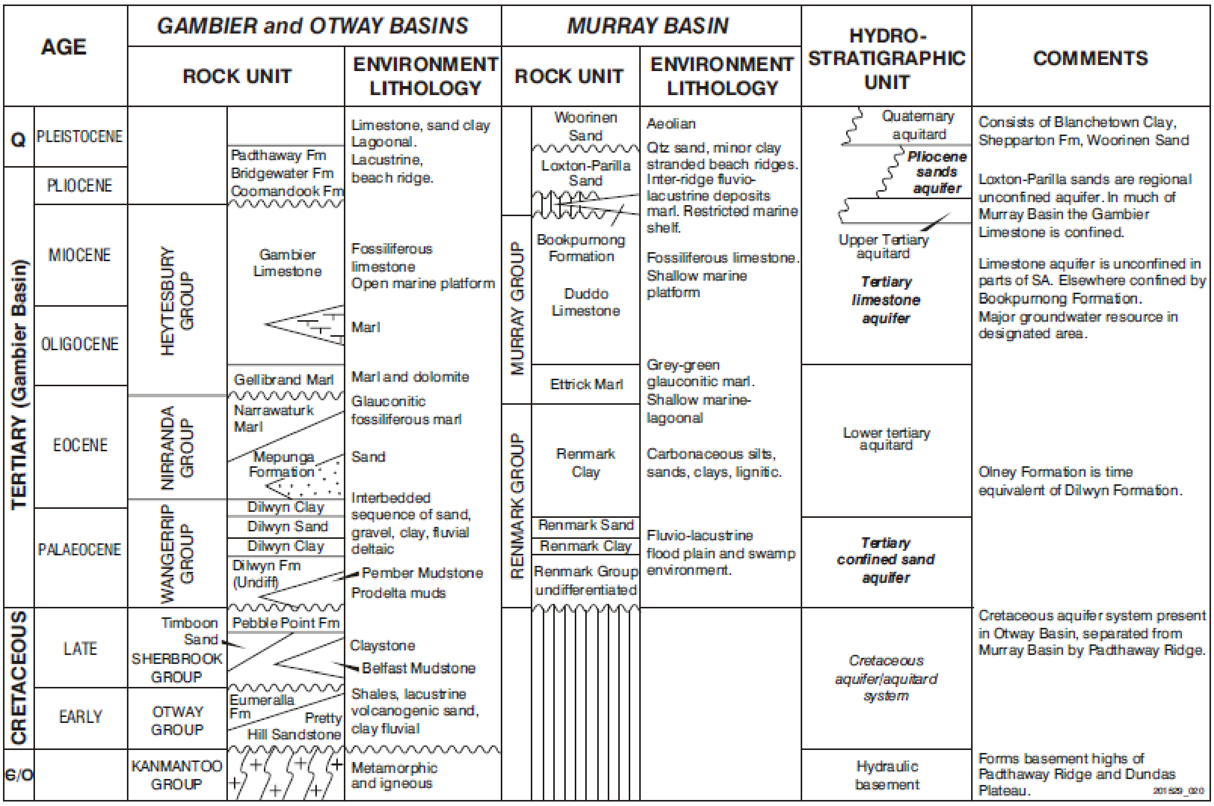


Figure 2 Stratigraphic and hydrostratigraphic units of the Otway, Gambier and Murray Basins (after Rammers and Stadter, 2002 and Lawson et al., 2009; original reference unknown).

2.2.2 SOUTH-WEST MARGIN OF THE MURRAY BASIN

The Murray Basin is a large, Cainozoic, intracratonic sedimentary basin located in south-eastern Australia (Brown, 1989; Rogers et al., 1995). It is one of the Tertiary continental margin basins of southern Australia, which formed at the start of the Mesozoic Era due to rifting between Australia and Antarctica (McLaren et al., 2011). The Murray Basin is the most laterally extensive of these basins, with an area of 300,000 km^2. Murray Basin sediments are comparatively thin, being no more than 600 m thick and mostly less than 200 m thick (Brown, 1989; McLaren et al., 2011).

The structural and stratigraphic framework of the Murray Basin is described in Brown (1989). The hydrogeology is described in greater detail in Evans and Kellett (1989). Lukasik and James (1998) revised the lithography and nomenclature of South Australian sediments of the Murray Supergroup. McLaren et al., (2011) summarised the current understanding of the palaeogeography, depositional environments and events of the south-western Murray Basin and the Western Otway Basin since the Late Miocene.

The Murray Basin contains two main sub-regions: the Riverine Plains in the east and the Mallee region in the west (Brown, 1989). Each sub-region features a local depocentre and is separated from the other by the Tyrell Fault and Neckarboo Ridge. Evans and Kellett (1989) further divided the Mallee region into two hydrogeological provinces: the Scotia province north of the Murray River and the Mallee-Limestone province south of the river.

The present study area includes the south-western margin of the Murray Basin, which is part of the Mallee region, and the Mallee-Limestone province. Within the study area, the Murray Basin abuts the Gambier Basin of the Otway Basin, the Grampians region and the Glenelg River region (Brown 1989). Most of the Murray Basin is bounded by Proterozoic and Palaeozoic fold belt rocks including the Dundas Plateau within the study area (Evans and Kellett, 1989). The Murray Basin is separated from the Gambier Basin by the shallow but largely concealed basement high of the Palaeozoic Padthaway Ridge (Brown, 1989; Lukasik and James, 1998); however, the stratigraphy of the two basins is considered equivalent.

The stratigraphy of the Mallee-Limestone province is summarised in Figure 2. The Renmark Group consists of predominantly fluvio-lacustrine sediments deposited in the Late Palaeocene to the Middle Eocene (Brown, 1989; Cobb and Barnett, 1994). During the Early Oligocene to Late Miocene the Ettrick Formation and Geera Clay were deposited in shallow to marginal marine environments. From the late Oligocene, Murray Group limestone was deposited in shallow marine environments (Brown, 1989). Pliocene marine transgression-regressions resulted in deposition of the Bookpurnong Beds and the Loxton-Parilla Sands (Brown, 1989). The Quaternary aeolian dunes of the Woorinen Formation represent reworkings of the Loxton-Parilla Sands (Evans and Kellett, 1989). The overlying Quaternary Bridgewater and Padthaway Formations occur in both the Murray Basin and the Gambier Basin within the Gambier coastal plain (McLaren et al., 2011).

2.3 Hydrogeology and Groundwater Flow

Groundwater in the study area occurs in a number of different hydrogeological systems in the Cainozoic and Cretaceous sequences. The Cretaceous aquifers are generally saline and too deep for economic utilisation (Love et al., 1993). Two major low salinity groundwater systems occur within the Cainozoic sequence: the Tertiary Confined Sand Aquifer system (TCSA), and the multi-lithological unconfined Tertiary Limestone Aquifer (TLA) system (Figure 2). The confined system comprises primarily the Dilwyn sand and clay units in the Gambier Basin and the Renmark Group Sands in the Murray Basin, and is separated in places from the underlying Cretaceous aquifers by the discontinuous Lower Tertiary Aquitard, comprising the Pember Mudstone; and from the overlying unconfined system by the Upper Tertiary Aquitard. In the Gambier Basin, the latter comprises the Narrawaturk Marl, the Mepunga Formation (which can occur as a discontinuous aquifer in some areas) and a clayey unit of the Dilwyn Formation itself, known as the Dilwyn Clay (Figure 2). In the Murray Basin, the Upper Tertiary Aquitard comprises the Ettrick Formation and Geera Clay.

The unconfined aquifer system in the Gambier Basin consists of the late Tertiary Gambier Limestone and the Quaternary age Padthaway and Bridgewater Formations. In the Murray Basin, it comprises the Duddo (Murray Group) Limestone, which can be overlain by the Bookpurnong Beds aquitard, the Loxton-Parilla Sands aquifer, the Blanchetown Clay aquitard and the Woorinen Sands. The Blanchetown Clay is not present in the study area as it was deposited further north, within the palaeo-lake Bungunnia (McLaren and Wallace, 2010). Detailed stratigraphic investigations in the southern part of the Gambier Basin have identified three sub-units in the Gambier Limestone, the Greenways, Camelback and Green Point members (Li et al., 2000; White, 2006)). The entire hydrogeological sequence of the Gambier Basin is wedge-shaped, thickening toward the south to up to 5 km offshore. The Cainozoic groundwater system itself can be up to 1000 m thick near the southern coast.

In the portion of the Murray Basin that occurs in the study area, groundwater in the Renmark Group and Murray Group aquifers generally flows in a westerly or north-westerly direction, away from the recharge areas of the southern Wimmera region located around the edges of the Dundas Plateau (Evans and Kellett, 1989). Other recharge areas for the Murray Group aquifer may include the Little Desert and local sinkholes (Evans and Kellett, 1989). Groundwater in the Loxton Sands aquifer, which is recharged by both rainfall and irrigation, flows in a north-westerly direction. Groundwater flows from the Riverine province into the Mallee-Limestone province within the Renmark and Loxton-Parilla Sands aquifers but not into the Murray Group aquifer, which does not extend laterally into the Riverine province (Evans and Kellett, 1989). Small volumes of flow occur out of the Murray Basin via the Renmark and Murray Group aquifers where they meet the coast over the Padthaway Ridge, including a portion of the study area (Evans and Kellett, 1989). In the Gambier Basin, groundwater in both the unconfined and confined aquifers generally flows toward the coast; from east to west in the region to the north of Mount Gambier and from north to south in the region to the south of Mount Gambier.

3 Hydrostratigraphic Model Development

3.1 Approach to simplified three-dimensional Hydrostratigraphic Model Development

3.1.1 LAYERS

The general approach applied to develop the simplified hydrostratigraphic units involved grouping formations broadly by geological age, as shown in Table 1.

Table 1 Gambier Basin and Murray Basin geological and hydrostratigraphic units and their representative layers in the preliminary hydrostratigraphic model.

HYDROSTRATIGRAPHIC MODEL LAYER	GEOLOGICAL UNIT (OTWAY BASIN)	GEOLOGICAL UNIT (MURRAY BASIN)	HYDROSTRATIGRAPHIC UNITS
1	Padthaway Fm Bridgewater Fm Coomandook Fm		Quaternary Limestone Aquifer
2	Gambier Limestone	Duddo Limestone (Murray Group)	Upper Mid-Tertiary Aquifer (Tertiary Limestone Aquifer - TLA)
3	Gellibrand Marl, Narrawaturk Marl, Upper Mepunga Fm	Geera Clay, Ettrick Formation, Renmark Clay	Upper Tertiary Aquitard
4	Lower Mepunga Fm		Lower Tertiary Aquifer
4	Dilwyn Sand Pember Mudstone Pebble Point Formation	Renmark Group Sand	Lower Tertiary Confined Aquifer (Tertiary Confined Sands Aquifer – TCSA)
5	Sherbrook Group	Cretaceous aquifer / aquitard system	Pre-Cainozoic Sediments and Basement

3.1.2 CREATION OF HYDROSTRATIGRAPHIC ELEVATION SURFACES

Several methods were used to create the hydrostratigraphic elevation surfaces for the simplified hydrostratigraphic three-dimensional model.

1. Extent of Simplified Hydrostratigraphic Units

The extent of simplified hydrostratigraphic units was developed from simplified geology GIS layers and from interpretation from prior projects in South Australia and Victoria, and identifies the extents of outcrop and subsurface features for each simplified hydrostratigraphic unit, as shown in Table 1.

2. Point Interpolation Data

Point elevation data was extracted from the NGIS Database (May 2013), which is based on data from DEWNR's SA

Geodata system, using SQL (Structured Query Language) queries in ArcGIS to obtain the top elevation (in mAHD) of generalised hydrostratigraphic units, e.g. Murray Group Limestone, Ettrick Formation, Renmark Formation and Basement (identified in borehole log data as map units), within the Murray-Otway Basin Region. Point data was also sourced from GHD Pty Ltd for the study area crossing into Victoria. Ground surface elevation was interpolated from the South Australian/Victorian state one second Digital Elevation Model (SA 1 Sec. DEM/Vic 1 Sec. DEM) (DEM).

3. Contour Interpolation Data

Contour data was used in conjunction with the point data. Contour data was provided by GHD Pty Ltd for the Victorian portion of the study area. Contour data was also obtained for the top of Cretaceous surface in the Otway Basin from Primary Industries and Regions SA (PIRSA).

4. Outcrop Features

Outcropping boundaries were determined by a combination of surface geology layers and geologists' interpretation of the data. The boundaries of the outcropping areas were converted to points and these points were given the value of the DEM at that point. The points were used in the interpolation process to 'pull the layer up' around the areas of outcrop. Outcropping features were created from the South Australian/Victorian state one second Digital Elevation Model (SA 1 Sec. DEM/Vic 1 Sec. DEM). The extents of outcrops were used to clip the 1 second DEM to create an outcrop surface elevation raster for the simplified hydrostratigraphic units.

5. Absent Areas

In the northern part of the study area on the South Australian side of the border, areas where units are absent were determined. These were also determined for the Victorian portion of the study area, near the border and around the Mount Gambier area using a Victorian interpretation of the extent of the stratigraphic units.

6. Subsurface Features

The ArcGIS 10.1 Topo to Raster (TTR) interpolation algorithm was used to interpolate elevation surfaces for each layer from the extracted NGIS point data. The TTR interpolation tool has been developed by the Australian National University to interpolate and hydrologically correct raster surfaces. The TTR interpolation method uses many types of input data commonly available such as contour lines, spot height data, fault lines, etc and considers the known characteristics of elevation surfaces. The TTR method uses an iterative finite difference interpolation technique. TTR is optimized to have the computational efficiency of local interpolation methods, such as inverse distance weighted (IDW) interpolation, without losing the surface continuity of global interpolation methods, such as Kriging and Spline. It is essentially a discretised thin plate spline technique for which the roughness penalty has been modified to allow the fitted elevation surface to follow abrupt changes in terrain, such as streams and ridges.

Additional data points were created along the boundaries of outcrop extents to assist the interpolation process. The height values for these points were obtained from the SA 1 Sec. DEM/Vic 1 Sec. DEM. The purpose of these additional points was to 'raise' the interpolated subsurface surface up to meet the outcrops.

The TTR interpolation produced the 'best fit' to the NGIS point height data when compared to IDW (Inverse Distance Weighted), Spline and Kriging interpolation methods available in ArcGIS 10.1, while also allowing the use of contour data. The default settings in the TTR tool allow sink features to be filled, which creates 'stream' features. In the case of interpolating subsurface elevations, the fill sink feature was disabled and therefore no artificial 'streams' have been created.

The subsurface elevation rasters were clipped (with a 100 m buffer, used to mosaic subsurface with outcrop extents) to their known extents, resulting in a subsurface elevation raster for the simplified hydrostratigraphic units.

7. Mosaic of Subsurface and Outcrop Extents

ArcGIS 10.1 was used to mosaic the outcrop extents with the subsurface extents. Where the two extents overlapped (buffer zones as previously described) a surface elevation averaging method was used to determine surface elevation.

8. Overcoming Problems Encountered with the Interpolated Elevation Surfaces

Analysis of the raster elevation surfaces was conducted to identify areas where subsurface features intersected/breached overlying elevation surfaces. An 'error' raster was created by subtracting the subsurface elevation raster from overlying surface elevation rasters using ArcGIS 10.1 Raster Calculator. The negative values in the resulting calculated raster indicated areas where subsurface elevation rasters were intersecting/breaching overlying elevation surfaces. Overlaying the interpolation point data on the 'error ' raster identified that the errors were either due to some areas of the outcropping extent 'ramping up ' and breaking the surface prematurely, a lack of point data, and/or possible errors within the borehole log information of the point data.

9. Indentifying and correcting errors within the borehole log information

Analysis of the borehole log information identified that misinterpretation and errors were present. Dubious borehole log data was either reinterpreted/adjusted or deleted/ignored. A re-run of the interpolation method, once a data cleansing was completed through SA GeoData (which is used to update the NGIS database nightly), demonstrated that cleansing the borehole log information decreased the amount of error (subsurface elevation rasters intersecting overlying elevation surfaces).

10. Resolving lack of point data and other areas of error

Errors in the interpolated elevation surface rasters attributed to a lack of point data or other unknown reasons were adjusted by forcing the subsurface elevation raster below overlying rasters using a condition statement in ArcGIS 10.1 raster calculator. The condition statement entered into the raster calculator altered any cell within the subsurface raster that had a height value higher than the overlying raster cell to be 3 m below the overlying cell.

3.2 Initial Checking and Modifications

Cross-sections and raster surfaces (Appendix A) from the preliminary hydrostratigraphic model were checked against existing cross-sections from DEWNR reports and hydrogeological maps, and reviewed by local hydrogeologists with expertise in the South East. Some areas for correction were identified. These were:

- The surface for the bottom of the TCSA/top of Pre-Cainozoic sediments and Basement contained a number of sharply sloping features, which were considered to be unrealistic and probably an artefact of the interpolation method, using a combination of point data and structural contours. These have been amended in the current model shown in Figure 3.
- Some areas along the SA/Victorian border, where the preliminary hydrostratigraphic model showed the Tertiary Limestone Aquifer and the Upper Mid-Tertiary Aquitard to be absent were considered to be questionable based upon local experience.

These issues were rectified as described below.

- Top of layer 1 – DEM: No changes were made to this surface.
- Top of layer 2 – Murray Group Limestone /Gambier Limestone: Additional data points were used to modify this surface so that the Gambier Limestone would be present in the south-eastern part of the study area. The surface was re-interpolated using the GIS model builder tool.
- Top of layer 3 – Ettrick Formation/Dilwyn Clay: Based on local knowledge, it was agreed that the aquitard should be continuous across the entire study area, except where the basement outcrops. Additional data points for the top of Dilwyn Clay were obtained from SA Geodata. This surface was re-interpolated using the GIS Topo to Raster tool.

- Top of layer 4 – Renmark Group/Dilwyn Sands: The discontinuous surface in the south-eastern part of the study area was made continuous. This was a minor change and did not require re-interpolation.
- Top of layer 5 – Basement: Elevation contours based on seismic surveys and petroleum well data obtained from the Department of State Development were included in the re-interpolation of this surface. In addition, some contours containing outlier values were also removed. This surface was re-interpolated using the GIS Topo to Raster tool.

Where major changes had been made, and unless otherwise specified, the surfaces were re-interpolated using the GIS model builder tool developed during Phase 1 of the project. A GIS technician's notes describing the methodology used in this process is provided as Appendix B. The tool used DEM values where the formation outcrops to the surface. The surface was then resampled to 200 m x 200 m and re-projected to MGA Zone 54. All surfaces were checked for negative thicknesses using another GIS model builder tool developed during Phase 1. Any negative thicknesses were changed to a thickness of 3 m, which was consistent with the Phase 1 approach. The sedimentary layers were represented as being absent where the basement outcrops.

3.3 Summary of the Final Hydrostratigraphic Model Product

The final hydrostratigraphic model (Figure 3) includes the following datasets:

<u>Topographic Surface</u>

- SA/VIC State 1 second Digital Elevation Model (DEM)

<u>Top of Layer 2 (Top of Gambier / Murray Group Limestone)</u>

- 2697 stratigraphic data points for the South Australian portion of the model domain.
- 209 stratigraphic data points for the Victorian portion of the model domain

<u>Top of Layer 3 (Top of Aquitard)</u>

- 733 data points for the whole model domain, including Victoria.

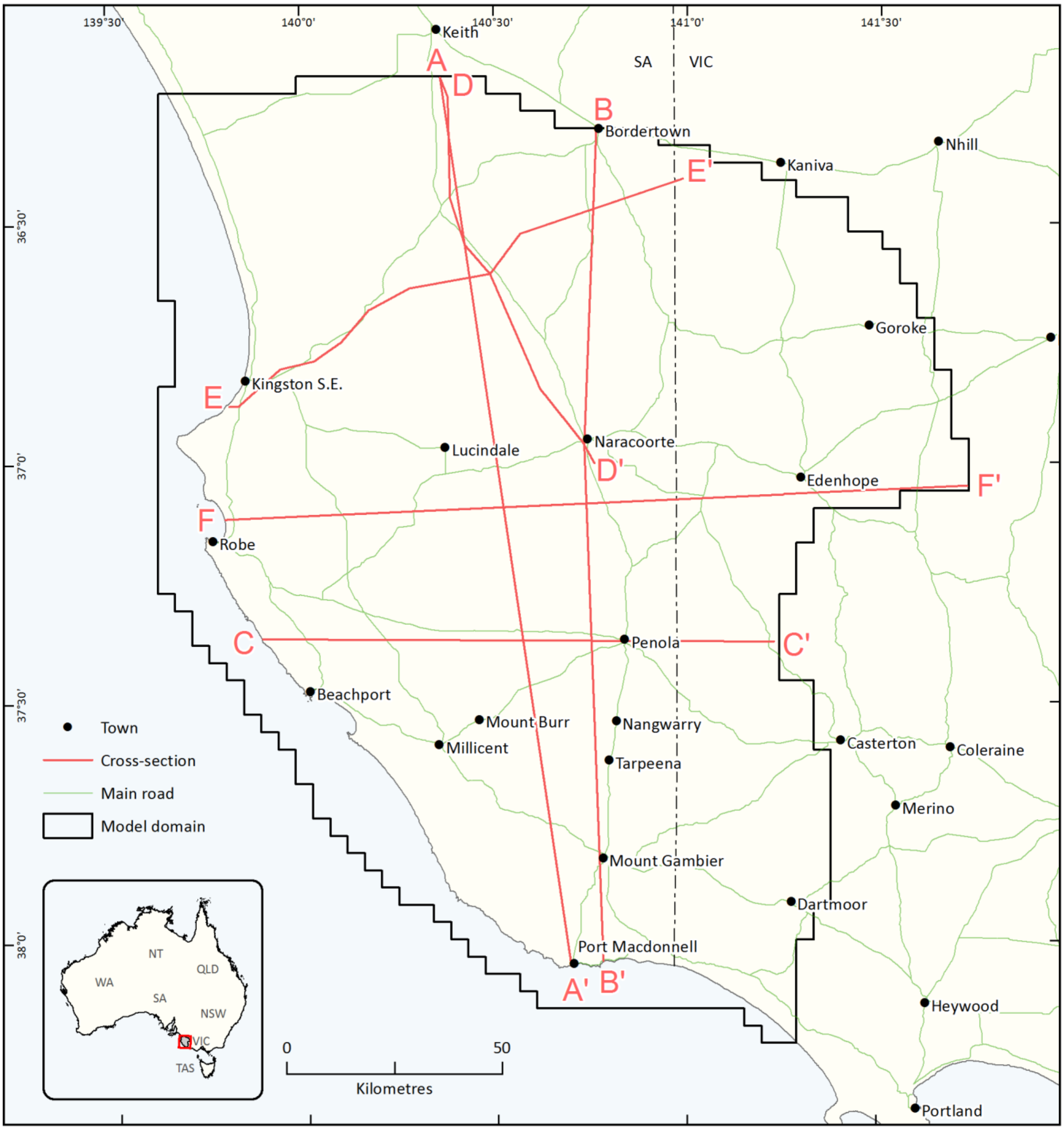
<u>Top of Layer 4 (Top of Dilwyn Sand / Renmark Group) – Layer 4 includes the Pember Mudstone and pebble Point Formations.</u>

- 874 stratigraphic data points for the South Australian portion of the model domain.
- 83 stratigraphic data points for the Victorian portion of the model domain

<u>Top of Layer 5 (Top of Basement)</u>

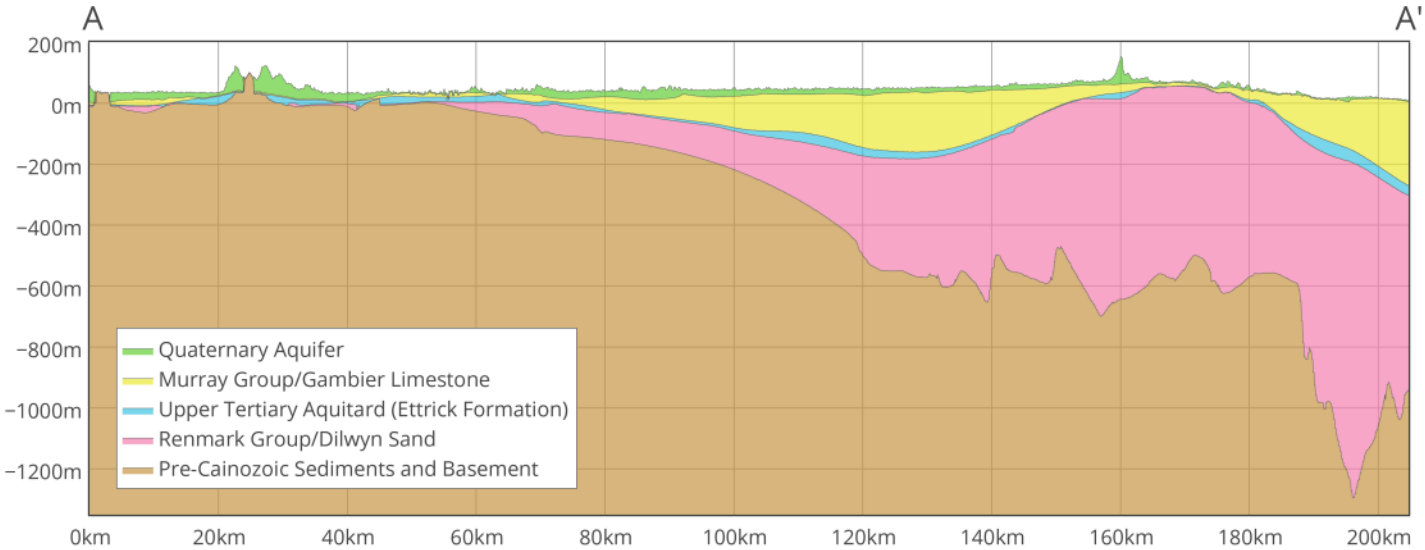
- 243 points for the South Australian portion of the study area. These were restricted to the Murray Basin (northern) portion of the study area.
- Contours of basement outcrops in the northern part of the SA portion of the study area.
- Contours derived from petroleum well and seismic data for the southern portion of the South Australian part of the study area.
- 63 points on the Victorian portion of the study area.

The final hydrostratigraphic surfaces have been stored in raster format in an ArcGIS geodatabase. The parent datasets described above are also available in ArcGIS formats.

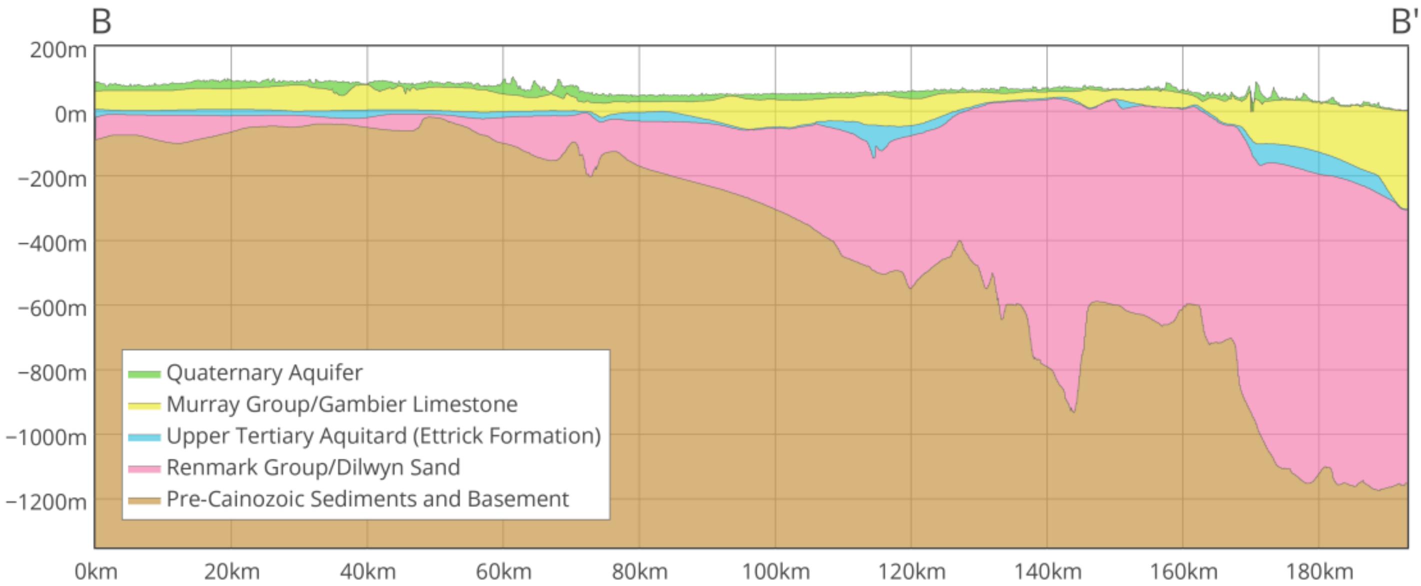


(a)

Figure 3 (a) Cross-section location map, and (b-f, below) cross-sections extracted from the preliminary hydrostratigraphic model.

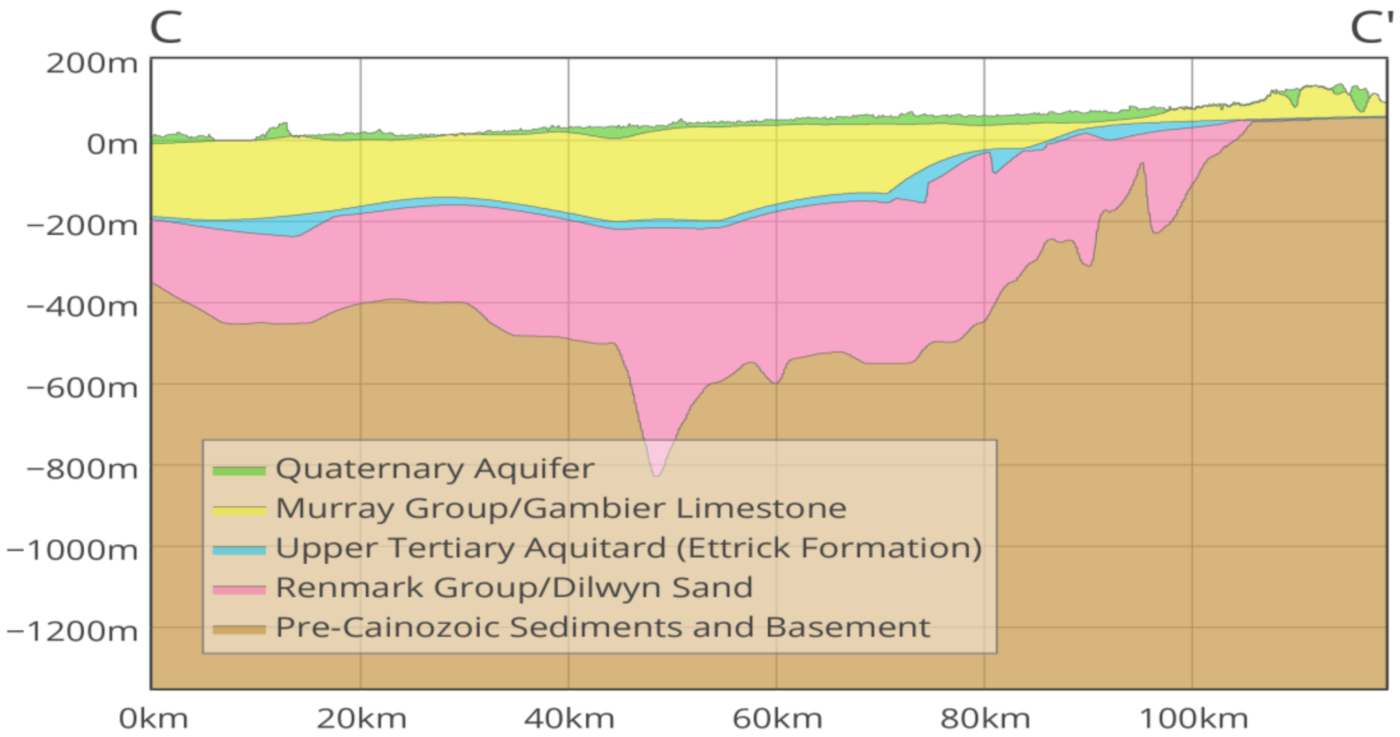


(b)

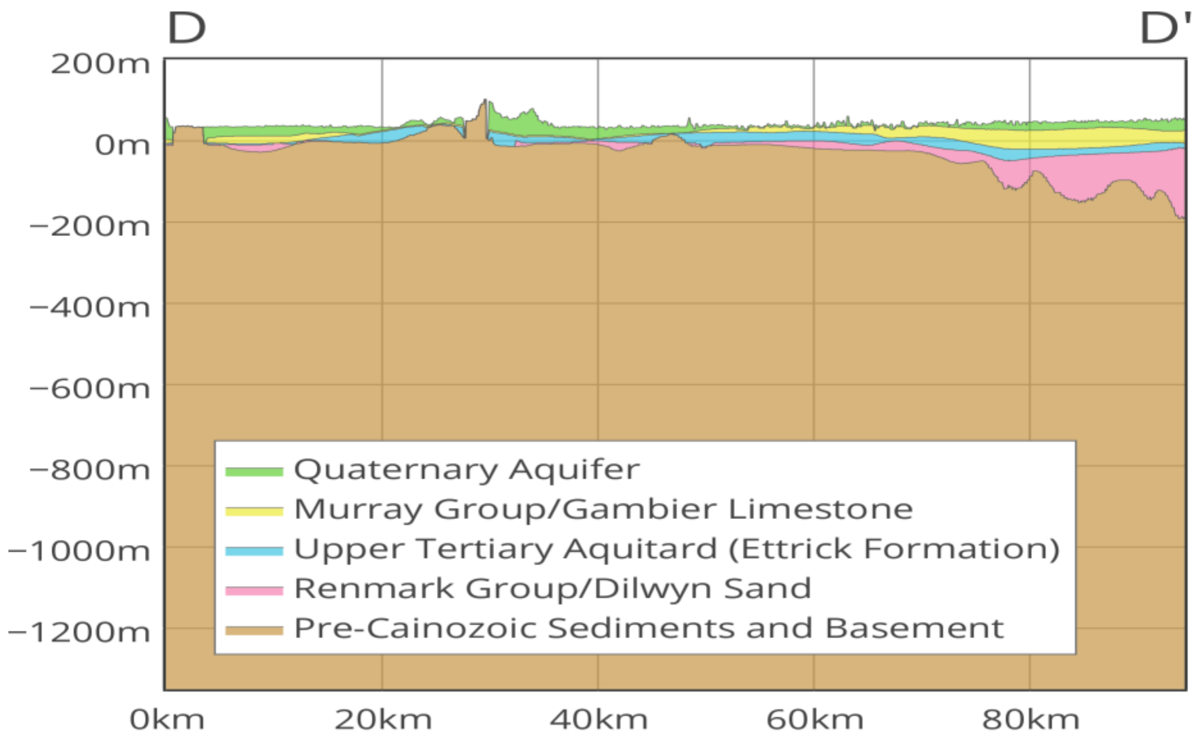


(c)

Figure 3 continued

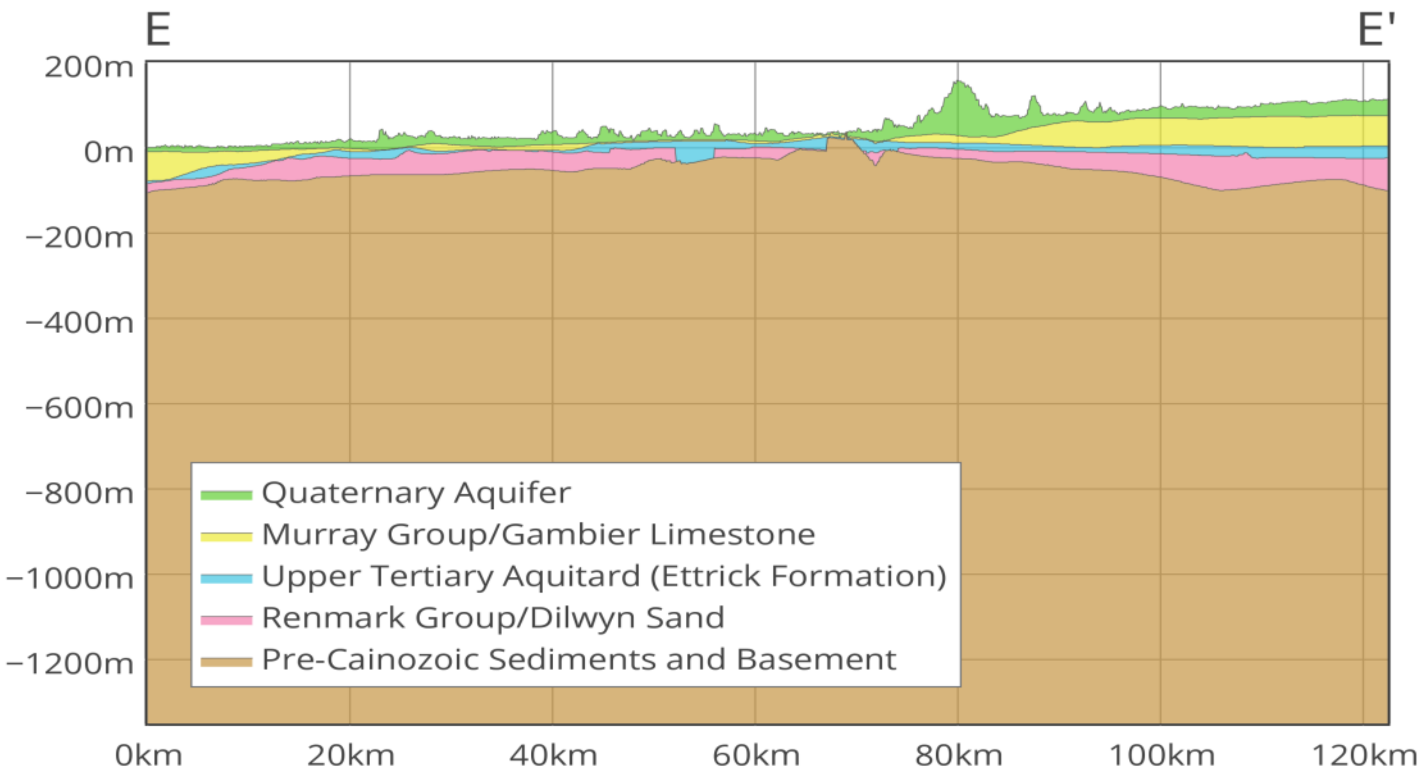


(d)

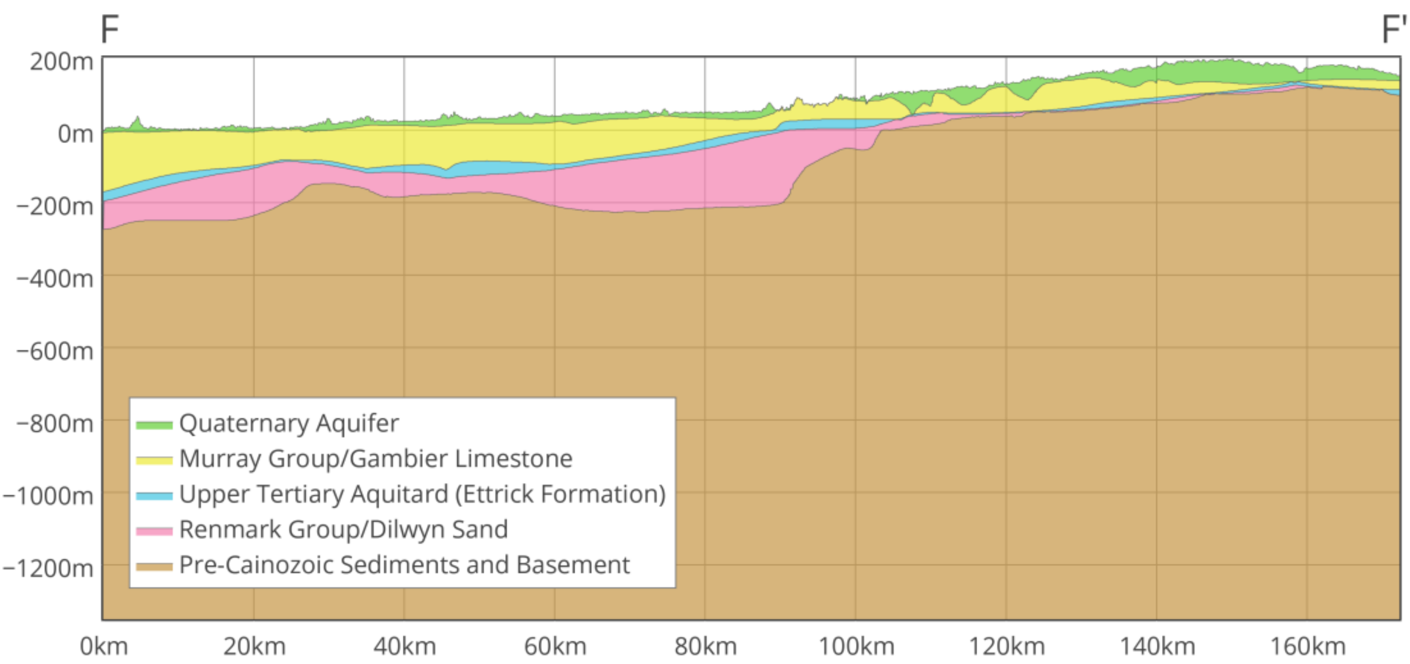


(e)

Figure 3 continued



(f)



(g)

Figure 3 continued

3.4 Testing of the Hydrostratigraphic Model in a Groundwater Model Framework

3.4.1 GROUNDWATER MODEL OVERVIEW

As described in Chapter 1, the hydrostratigraphic model was developed in collaboration with the South East Regional Water Balance (SERWB) project, and the domain of the stratigraphic model was governed by the domain of the regional groundwater model being developed for that project. The hydrostratigraphic model was used to develop the three-layer model grid for the groundwater flow model and, during this process, the hydrostratigraphic model underwent various types of testing to check the validity of the layers. This is also described in the groundwateter model development report (Morgan et al., in prep.). However, as the results of this testing process are relevant to the hydrostratigraphic model product itself, it is described below. The broad details of the groundwater flow model are provided below.

The regional groundwater flow model for the South East Regional Water Balance Project was developed in the MODFLOW code (Harbaugh et al., 2000) using the Groundwater Vistas Graphical User Interface (GUI) (Rumbaugh and Rumbaugh, 2011). The model domain, which is shown in Figure 1, was chosen to include the area of interest, which is the Lower Limestone Coast Prescribed Wells Area, but to incorporate the whole regional groundwater flow system, being generally bounded by groundwater no-flow boundaries. The model includes three layers:

- Layer 1: The unconfined aquifer system, including the Tertiary Limestone Aquifer (TLA) and the quaternary aquifers (Hydrostratigraphic model Layers 1 and 2).
- Layer 2: the Tertiary aquitard (Hydrostratigraphic model Layer 3).
- Layer 3: the Tertiary Confined Sand Aquifer (TCSA) system (Hydrostratigraphic model Layer 4).

Because of the large scale of the groundwater flow model (approximately 200 km x 200 km), a model grid size of 1 km x 1 km was implemented to minimise run-times. This grid size is considered to be sufficient to achieve objectives of the groundwater flow model, which are to answer questions about the regional water balance (refer to SE Water Balance Phase 2 report, in preparation).

3.4.2 CREATION OF MODEL LAYER SURFACES FROM THE HYDROSTRATIGRAPHIC MODEL

To create the model layers, the model cell nodes were exported as a shape file from Groundwater Vistas. The surface elevation values were then extracted to the model cell nodes using the “Extract values to points” tool in ArcGIS. All the optional functions such as interpolation were turned off when executing this tool. For the purpose of importing into the model, the SA/VIC State 1 second DEM raster was used, which has a resolution of approximately 25 m x 25 m.

Locations where the unconfined aquifer (Layer 1) is absent were identified. At these locations, the aquitard (Layer 2) and confined aquifer (Layer 3) are also absent and basement outcrops.

In the groundwater flow model, inactive model cells (i.e., where the basement outcrops) were assigned the following elevations for visualisation purposes (this has no impact on the model results):

Top of Layer 1: 0 m AHD

Top of Layer 2: -1 m AHD

Top of Layer 3: -2 m AHD, except when overlying cells for layer 1 are active, then Top Layer 3=Top Layer 2 -1 m (this was done for visualisation purposes, so that the thickness of layer 2 is 1 m when it is inactive, and therefore appears very thin)

Bottom of Layer 3: -3 m AHD, except when overlying cells for layer 1 are active, then Bottom Layer 3 = Top Layer 2 -2 (again, this was done for visualisation purposes, so that the thickness of layer 3 is 1 m when it is inactive, and therefore appears very thin).

When Layer 3 is absent, Layer 2 is also always absent in the model. However, Layer 3 is absent in locations where Layer 1 is present. The new layers were imported into Groundwater Vistas.

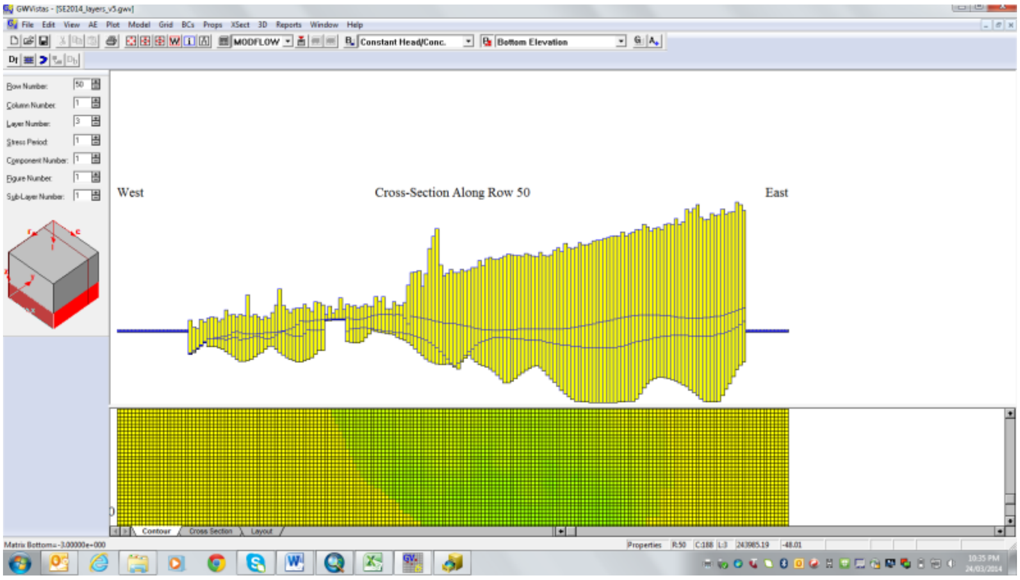


Figure 4 Screen capture showing an example cross section from the groundwater model in Groundwater Vistas, with the three groundwater model layers shown.

3.4.3 EVALUATION OF MODEL LAYER THICKNESSES

Maps of model layer thicknesses were developed to:

1) Ensure that manipulation and contouring of the data had not resulted in negative layer thicknesses.
2) Assist local expert hydrogeologists in the assessment of aquifer thicknesses across the study area.

Model layer thicknesses were obtained by editing a text file, derived from a shapefile of model layer elevations. When a layer is absent a thickness value of 0 was assigned.

These files were used to create contours in the Surfer contouring software, which were then imported into Arc Map to develop graphical illustrations of model layer thicknesses (Figures 5 - 7). There were no apparent issues with the layer thicknesses in the groundwater model, meaning no changes to the hydrostratigraphic model were required.

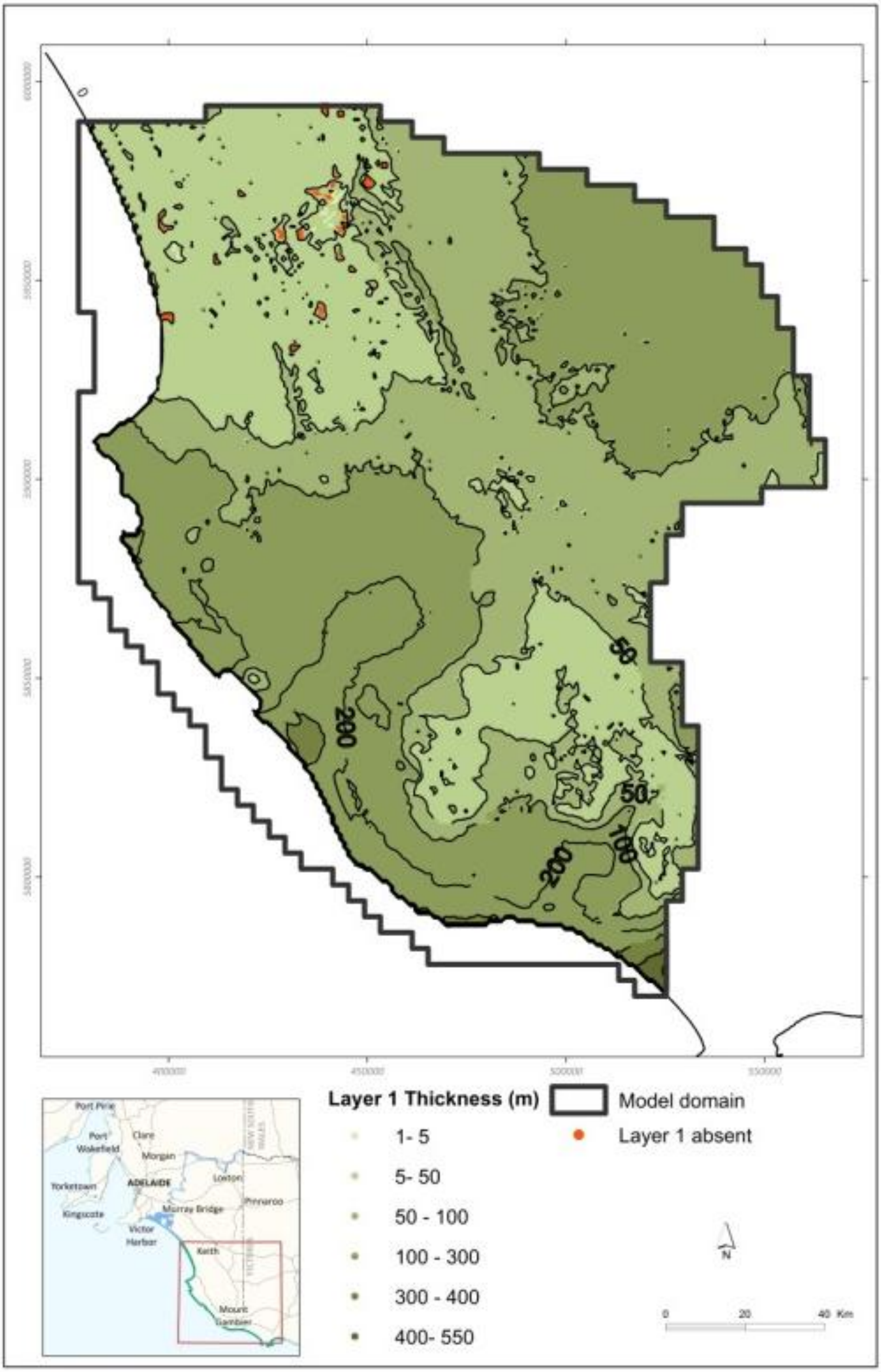


Figure 5 Model layer 1 thickness.

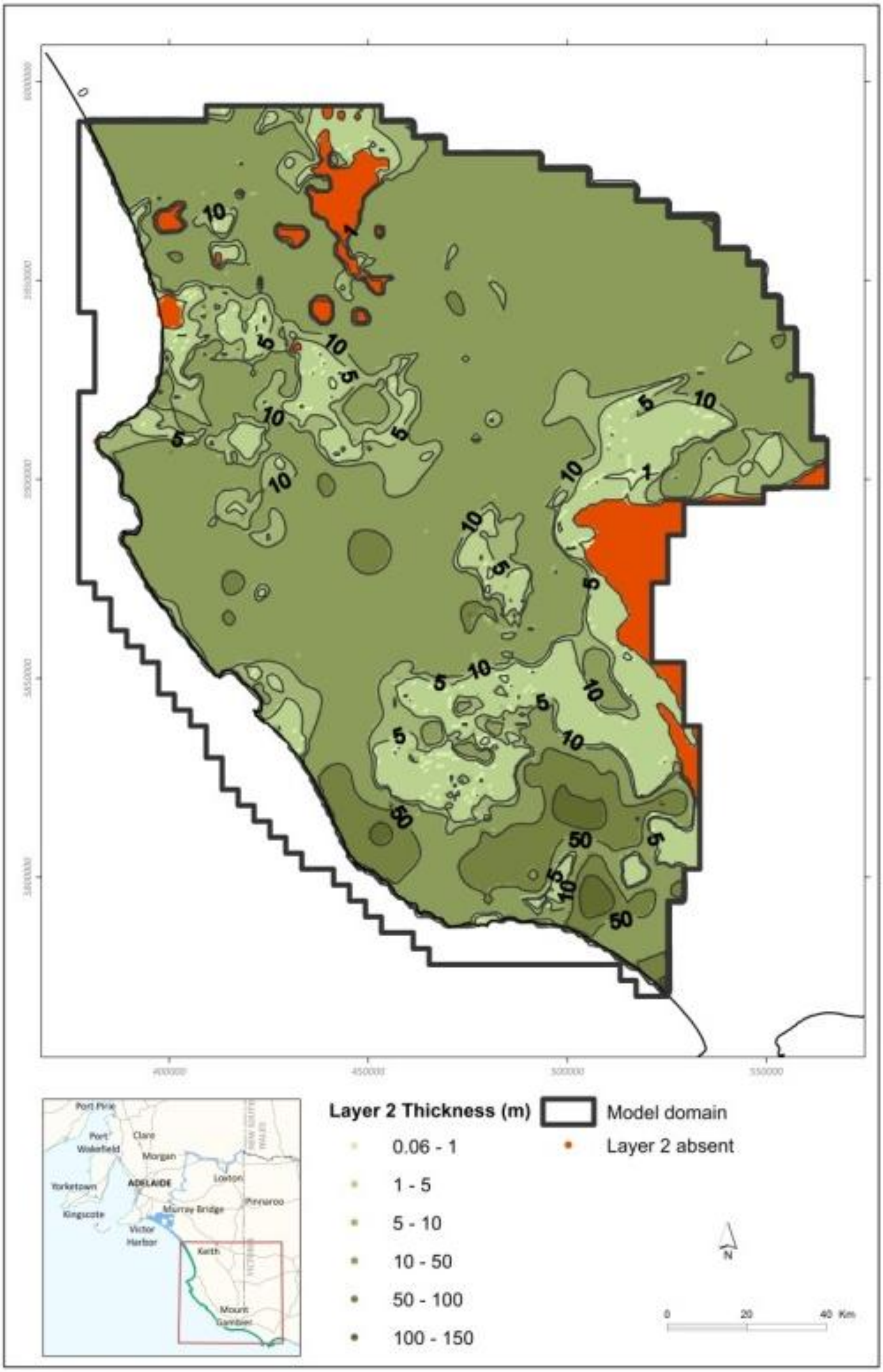


Figure 6 Model layer 2 thickness.

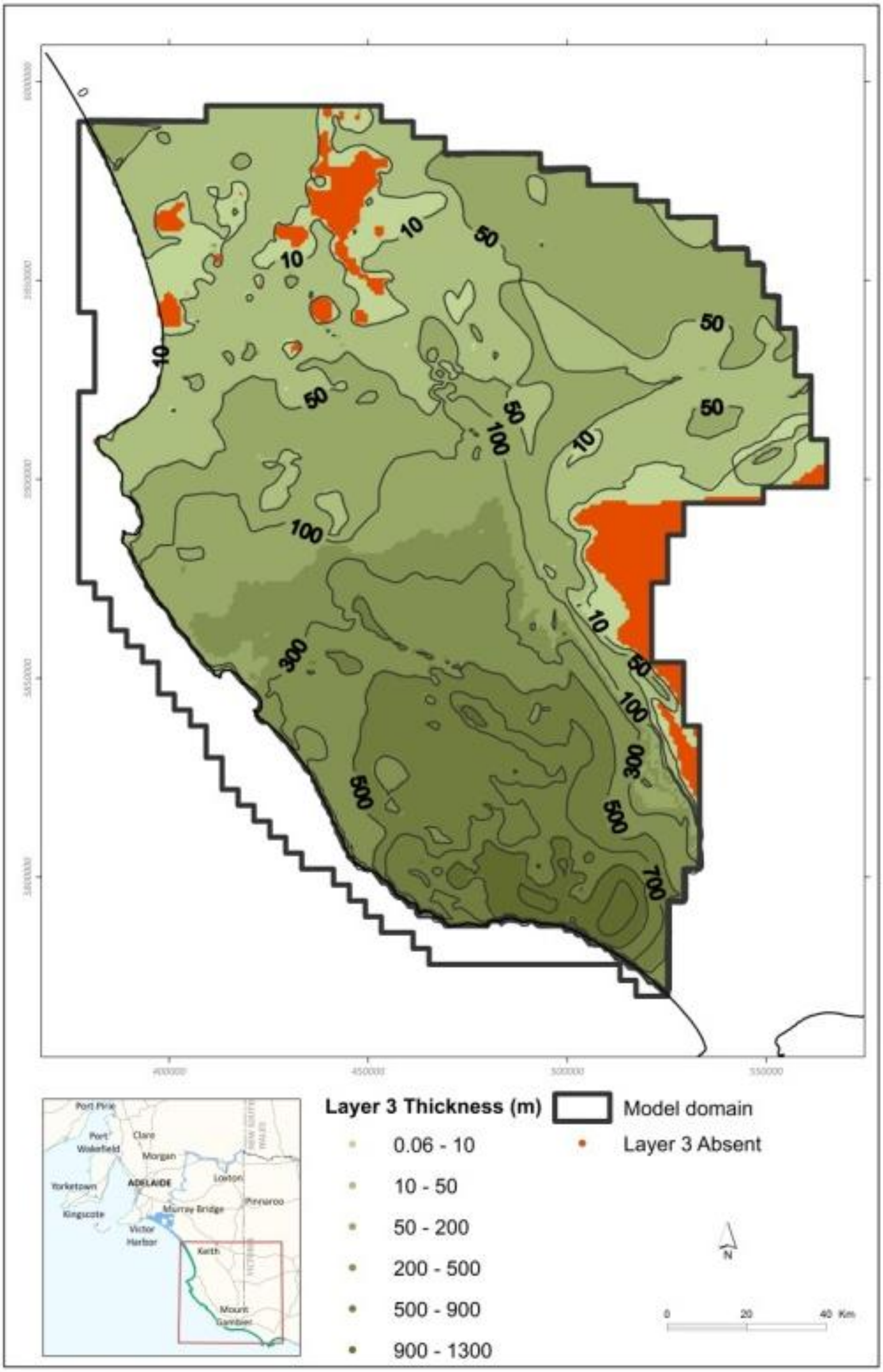


Figure 7 Model layer 3 thickness.

3.4.4 EVALUATION OF SATURATED THICKNESS OF LAYER 1

The saturated thickness of Layer 1 was evaluated to:

1) Identify areas where Layer 1 may be dry in the groundwater flow model.
2) Compare areas where the water table is above the land surface with mapped surface water features.
3) Through (1) and (2) identify any areas of the hydrostratigraphic model that may contain errors.

The datasets used in the evaluation were:

1) Unconfined aquifer observation well data for September 2011 (Figure 11).
2) The Layer_2_Top shapefile, which is the top of Layer 2 (base of unconfined aquifer) calculated for the model grid (1 km x 1 km grid spacing). Here the elevation value at the cell centre was used.
3) The Layer_1_Top shapefile, which is the top of Layer 1 (taken from DEM) calculated for the model grid (1 km x 1 km grid spacing). Here the elevation value at the cell centre was used.

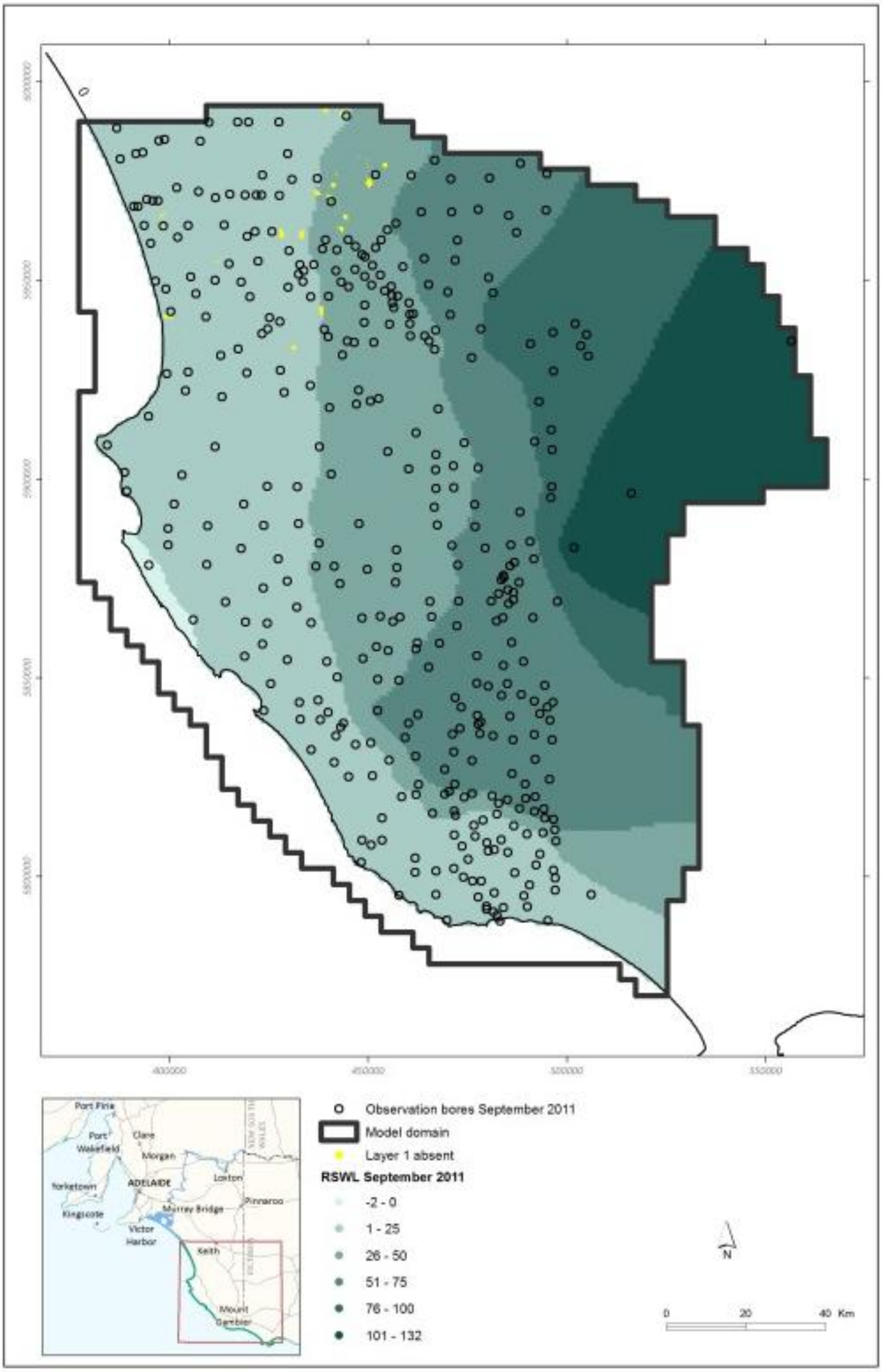


Figure 8 RSWL m AHD September 2011 Layer 1.

Figure 9 shows the calculated saturated thickness of Layer 1, with implied dry areas indicated in pink. The limitations of this analysis should be noted, with the largest being that the water table surface used is created from observation well data, which can be sparse in some points and interpolation between these points limits the accuracy of the results. The analysis indicates two areas in the model domain where the unconfined aquifer may be dry. The first occurs in the north of the model domain, in the area where the basement outcrops and this is not unexpected. The second area, located in the south of the model domain was investigated more closely. Interpolation of the water table surface was not likely to be a major source of error in this region, as there were water level data points close to the apparently dry area. DEWNR staff have made some observations in this area, and agree that the saturated thickness of the aquifer can be less than 10 m, although complete dryness has not been observed. This area of potential dryness in the unconfined aquifer has been noted for consideration in the interpretation of groundwater model results.

Figure 10 shows the depth to water table in Layer 1, with areas where the water table is above land surface identified in pink and red colours. Again, the limitations of using an interpolated water table surface in this analysis should be recognised. Figure 11 shows the depth to water table map, with an overlay of the mapped waterbodies for the region. This figure shows that many of the areas where the water table is calculated to be above the ground surface correspond to mapped surface water bodies. However, there are some pink and red areas that do not correspond to mapped surface water bodies, particularly (a) in the first inter-dunal corridor to the east of Beachport and Robe, and (b) at the base of the Naracoorte Ranges, to the north-west of Naracoorte. Adding an overlay of the man-made surface drainage system and other watercourses for the South Australian portion of the study area (

Figure 12) identifies the reason that there is no mapped standing water at (a) despite the fact that the water table is inferred to be above ground level here. This area is drained by a complex system of man-made drains, which will be included as separate features in the groundwater flow model. However, the inferred above-ground water table at (b) is not explained by mapped surface water or man-made drainage features. This is likely to be due to interpolation of observation well data between the high elevation Naracoorte Ranges and the adjacent flats, hence this area has been identified for close scrutiny in the results of the groundwater flow model. The red area in the south-east (Victorian) portion of the study area is known to correspond to the Glenelg River valley. The positive results of this analysis also meant that no further changes to the hydrostratigraphic model were considered necessary for its application in the regional water balance model.

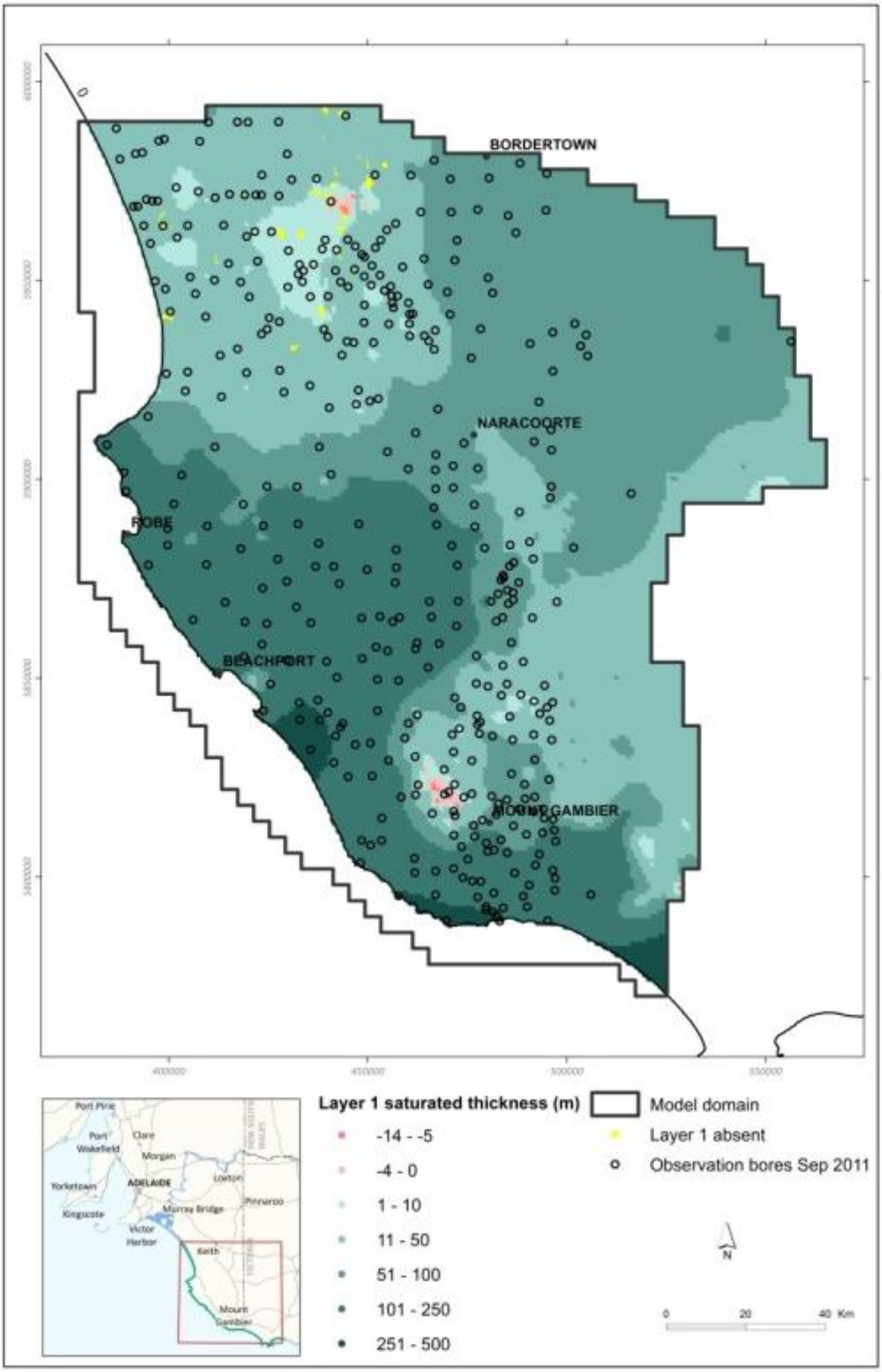


Figure 9 Layer 1 saturated thickness. Dry cell areas are indicated in pink.

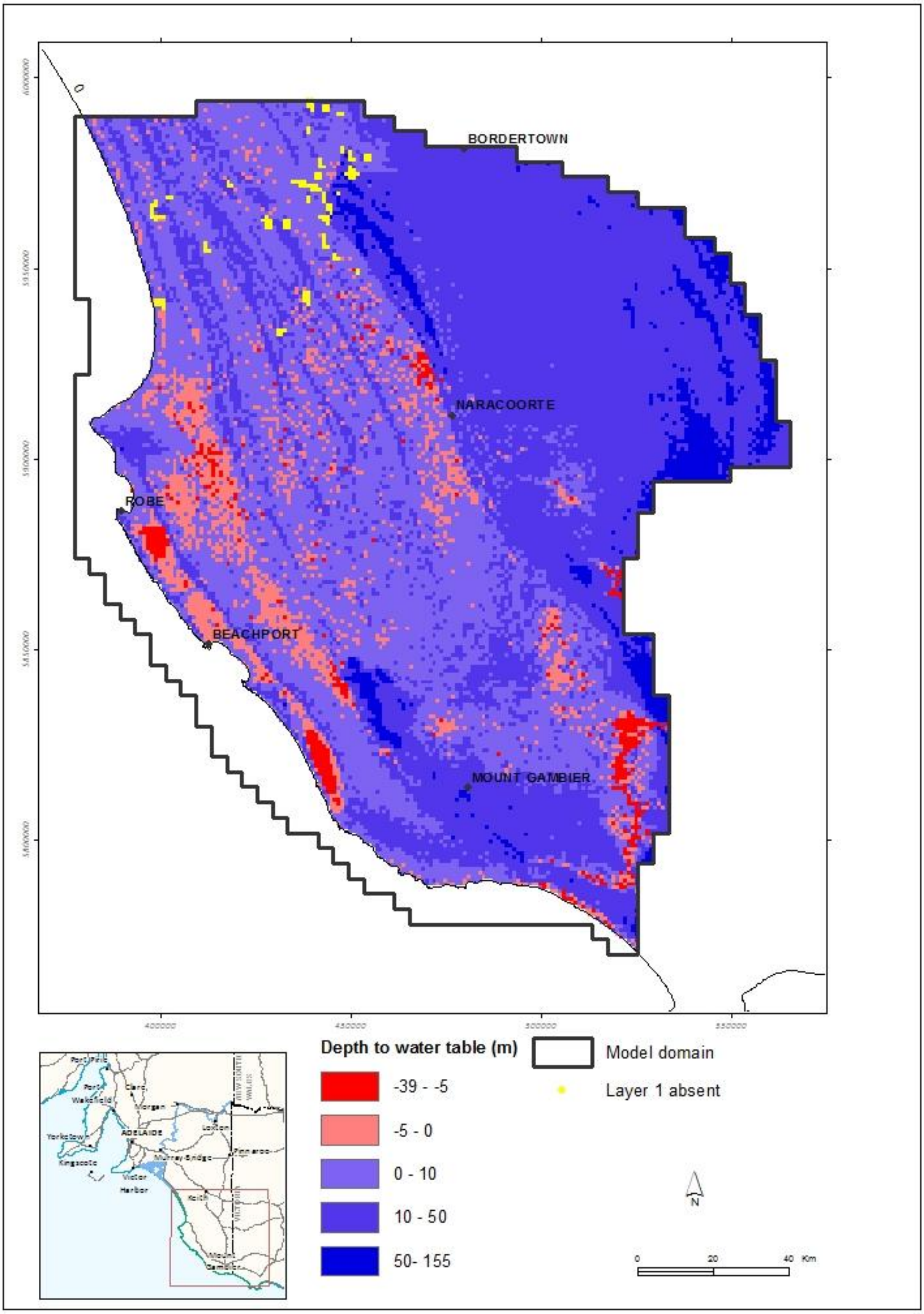


Figure 10 Layer 1 depth to water table, showing areas where water table is above land surface.

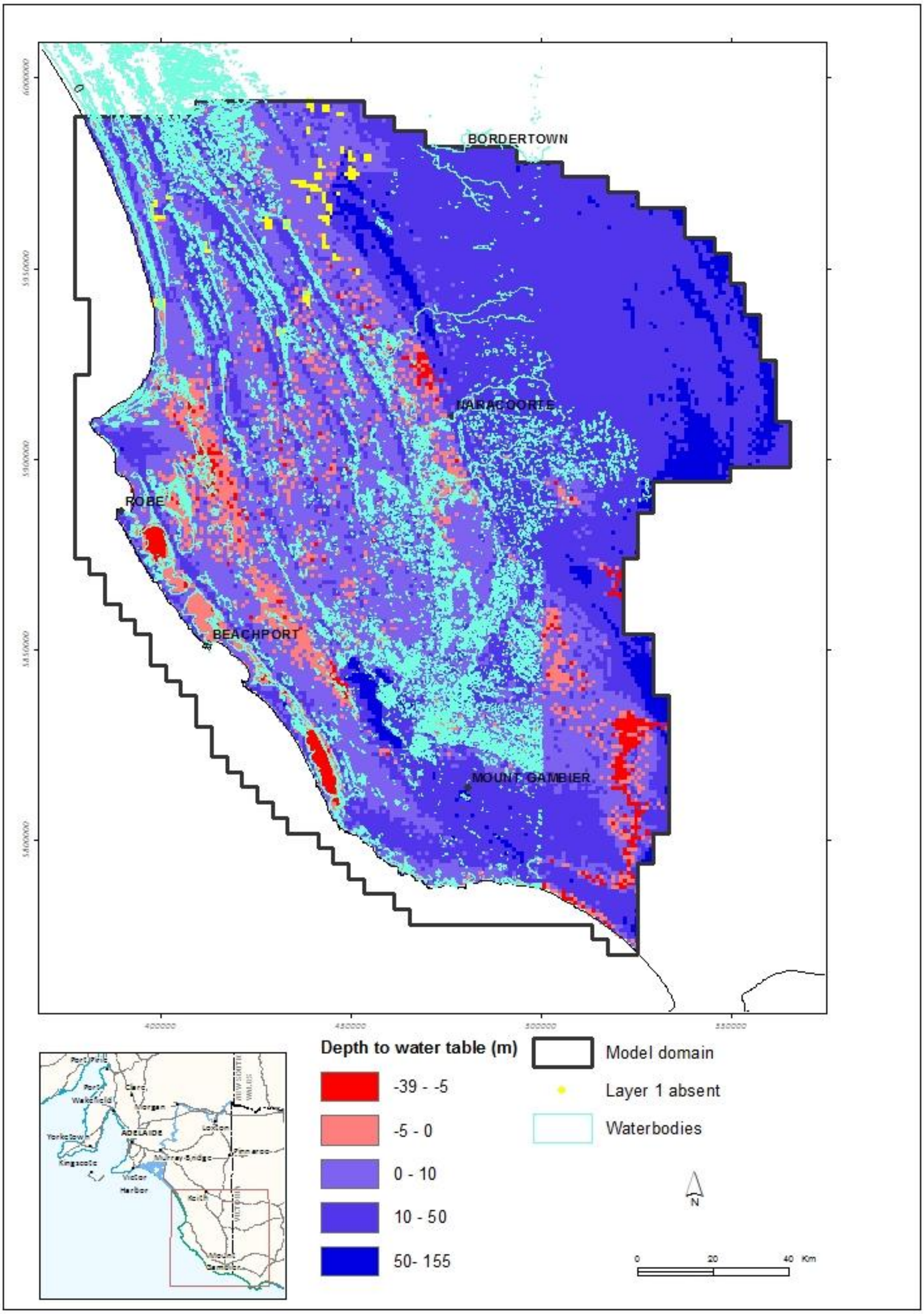


Figure 11 Layer 1 depth to water table, showing areas where water table is above land surface and outlines of mapped waterbodies.

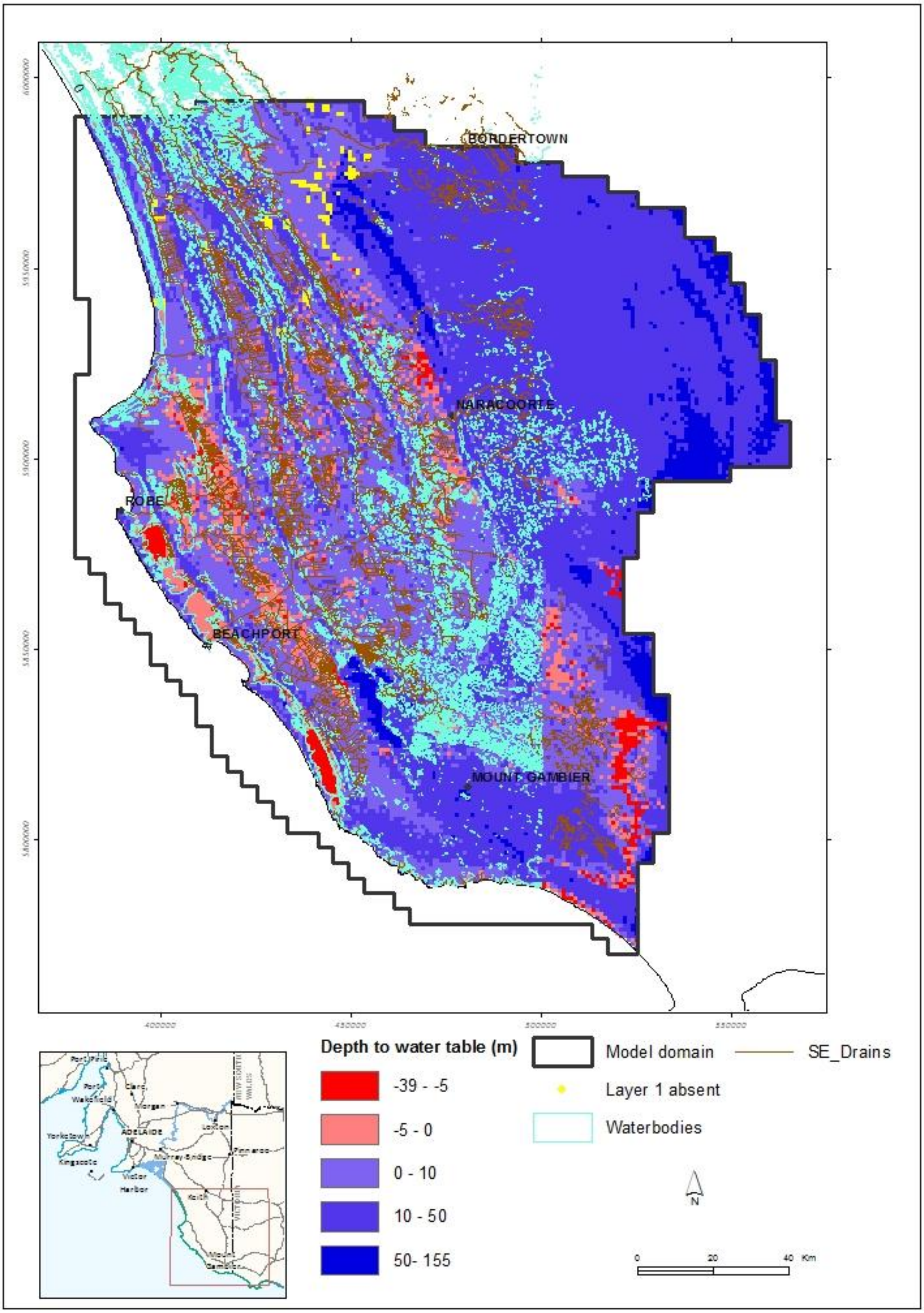


Figure 12 Layer 1 depth to water table, showing areas where water table is above land surface and outlines of mapped waterbodies, with man-made drains and watercourses also shown.

4 Conclusions and Future Work

A five-layer hydrostratigraphic model has been produced for the Gambier Basin and the south-western Murray Basin in an ArcGIS framework. The model is the first to cover both the South Australian and Victorian portions of this region and includes all currently available data. The model has been tested to the best of our ability by comparing:

(1) model layer thicknesses with the knowledge of local expert hydrogeologists;
(2) the base of Layer 2 (Lower Mid-Tertiary unconfined aquifer) with water table contours from September 2011 to identify possible dry regions in the unconfined aquifer, and
(3) the top of Layer 1 (surface topography) with the same water table contours to identify areas where the water table may be above ground (for comparison with mapped surface water bodies).

Implementation of the hydrostratigraphic model in a regional MODFLOW groundwater flow model has provided confidence that it is appropriate for groundwater flow modelling exercises, at least at the regional scale.

The hydrostratigraphic model could be improved in the future, particularly for the purpose of seawater intrusion and offshore groundwater flow investigations, by adding offshore data from petroleum wells, of which there is approximately 10 in the study area.

Results of any future drilling into the deeper aquifers (below the Tertiary Confined Aquifer) should also be included in the model, with these deeper layers added to the model, even if the data is sparse. The reason for this is that interactions between these deeper aquifers and the Tertiary Aquifer system are very poorly understood but cannot be ruled out. Any future investigations into these aquifer interactions may require these layers to be added to the hydrostratigraphic model.

5 References

Brown CM (1989) Structural and stratigraphic framework of groundwater occurrence and surface discharge in the Murray Basin, southeastern Australia. Journal of Australian Geology & Geophysics 11, 127-146.

Cobb MA and Barnett SR (1994) Naracoorte Hydrogeological Map (1:250000 scale). Australian Geological Survey Organisation, Canberra.

Evans WR and Kellett JR (1989) The hydrogeology of the Murray Basin, southeastern Australia. Journal of Australian Geology & Geophysics 11, 147-166.

Gravestock D, Hill A and Morton J (1986) A review of the structure, geology and hydrocarbon potential of the Otway Basin in South Australia. South Australian Department of Mines and Energy.

Harbaugh AW, Banta ER, Hill MC and McDonald MG (2000) MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- User guide to modularization concepts and the Ground-Water Flow Process. USGS.

Kenley P (1971) Cainozoic geology of the Eastern part of the Gambier Basin, south-western Victoria. In: Wopfner H and Douglas J (eds) The Otway Basin of South-eastern Australia. Geological Surveys of South Australia and Victoria, 89-144.

Lawson J, Mustafa S and Wood C (2009) Field investigations into the influence of faulting on groundwater flow and recharge of the Tertiary Limestone Aquifer, Lower South East, South Australia. DRAFT. South Australian Department for Water.

Li Q, McGowran B and White MR (2000) Sequences and biofacies packages in Mid-Cenozoic Gambier Limestone, South Australia; repraisal of foraminiferal evidence. Australian Journal of Earth Science 47, 955-970.

Love AJ, Herczeg AL, Armstrong D, Stadter F and Mazor E (1993) Groundwater flow regime within the Gambier Embayment of the Otway Basin, South Australia: Evidence from hydraulics and hydrochemistry. Journal of Hydrology 143(3-4), 297-338. DOI: 10.1016/0022-1694(93)90197-h.

Lukasik JJ and James NP (1998) Lithostratigraphic revision and correlation of the Oligo-Miocene Murray Supergroup, western Murray Basin, South Australia. Australian Journal of Earth Sciences 45(6), 889-902. DOI: Doi 10.1080/08120099808728443.

Mann B, Chaplin H and Stanley D (1994) Hamilton Hydrogeological Map (1:250000 scale). Australian Geological Survey Organisation, Canberra.

McLaren S and Wallace MW (2010) Plio-Pleistocene climate change and the onset of aridity in southeastern Australia. Global and Planetary Change 71(1-2), 55-72. DOI: 10.1016/j.gloplacha.2009.12.007.

McLaren S, Wallace MW, Gallagher SJ, Miranda JA, Holdgate GR, Gow LJ, Snowball I and Sandgren P (2011) Palaeogeographic, climatic and tectonic change in southeastern Australia: the Late Neogene evolution of the Murray Basin. Quaternary Science Reviews 30(9-10), 1086-1111. DOI: DOI 10.1016/j.quascirev.2010.12.016.

Morgan, LK, Harrington, N, Werner, AD, Hutson, JL, Woods, J and Knowling, M, in prep., *South East Regional Water Balance Project – Phase 2. Development of a Regional Groundwater Flow Model.* Goyder Institute for Water Research Technical Report.

Rammers N and Stadter F (2002) South East Prescribed Wells Areas groundwater monitoring status reports 2002 South Australia. Department of Water, Land and Biodiversity Conservation.

Rumbaugh J and Rumbaugh D (2011) A Guide to Using Groundwater Vistas Version 6. Environmental Simulations Inc.

Ryan SM, Knight LA and Parker GJ (1995) The Stratigraphy and Structure of the Tyrendarra Embayment, Otway Basin, Victoria. Department of Agriculture, Energy & Minerals, Victoria.

SKM (2009) Glenelg Hopkins CMA Groundwater Model. Department of Sustainability and Environment, Victoria.

Smith P, Rogers P, Lindsay J, White M and Kwitko G (1995) Gambier Basin. In: Drexel J and Preiss W (eds) The Geology of South Australia: Vol. 2. The Phanerozoic. . South Australia Geological Survey, Adelaide, Australia, 151– 156.

Appendix A Raster surfaces for the preliminary hydrostratigraphic model.

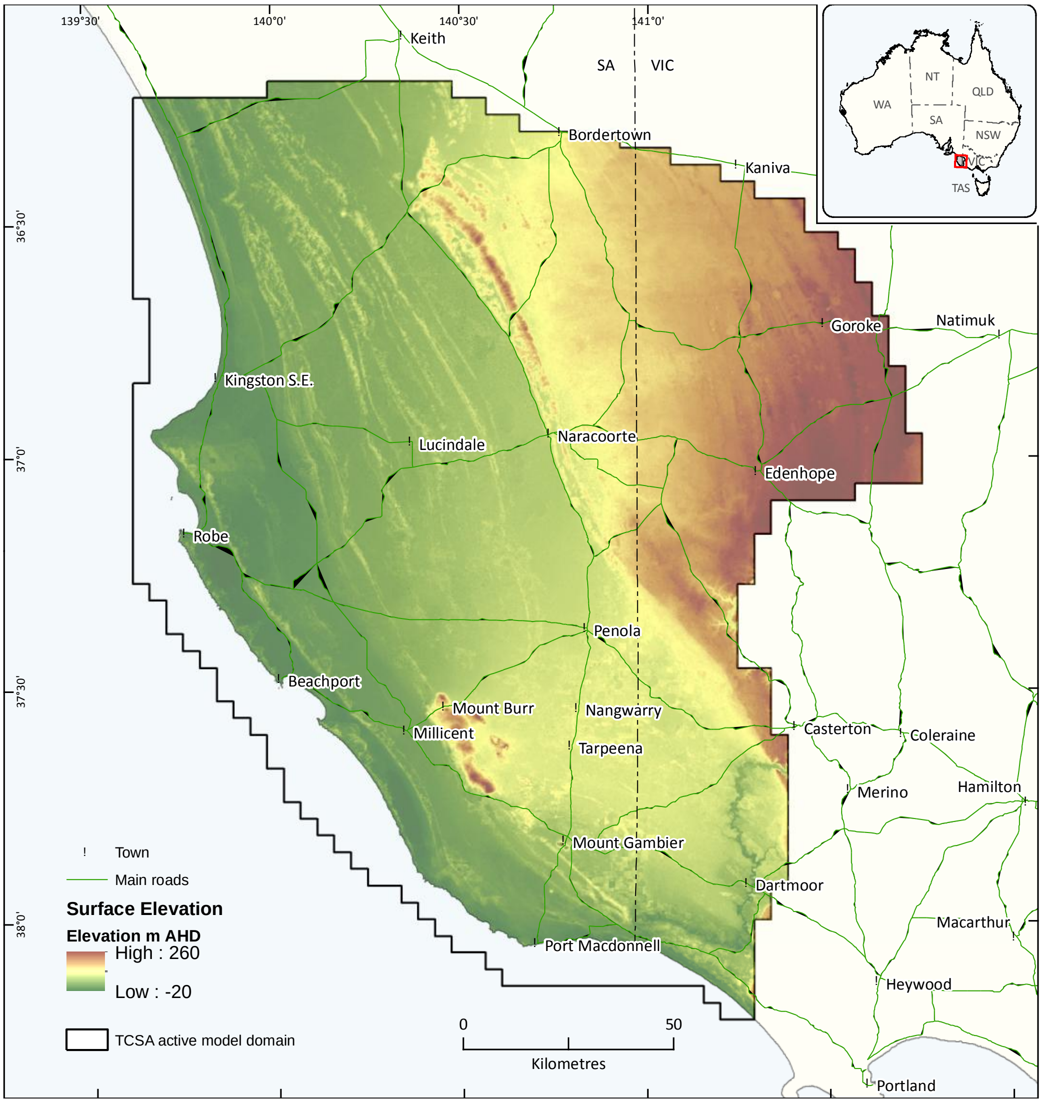


Figure A1. Topographic surface (top of Layer 1).

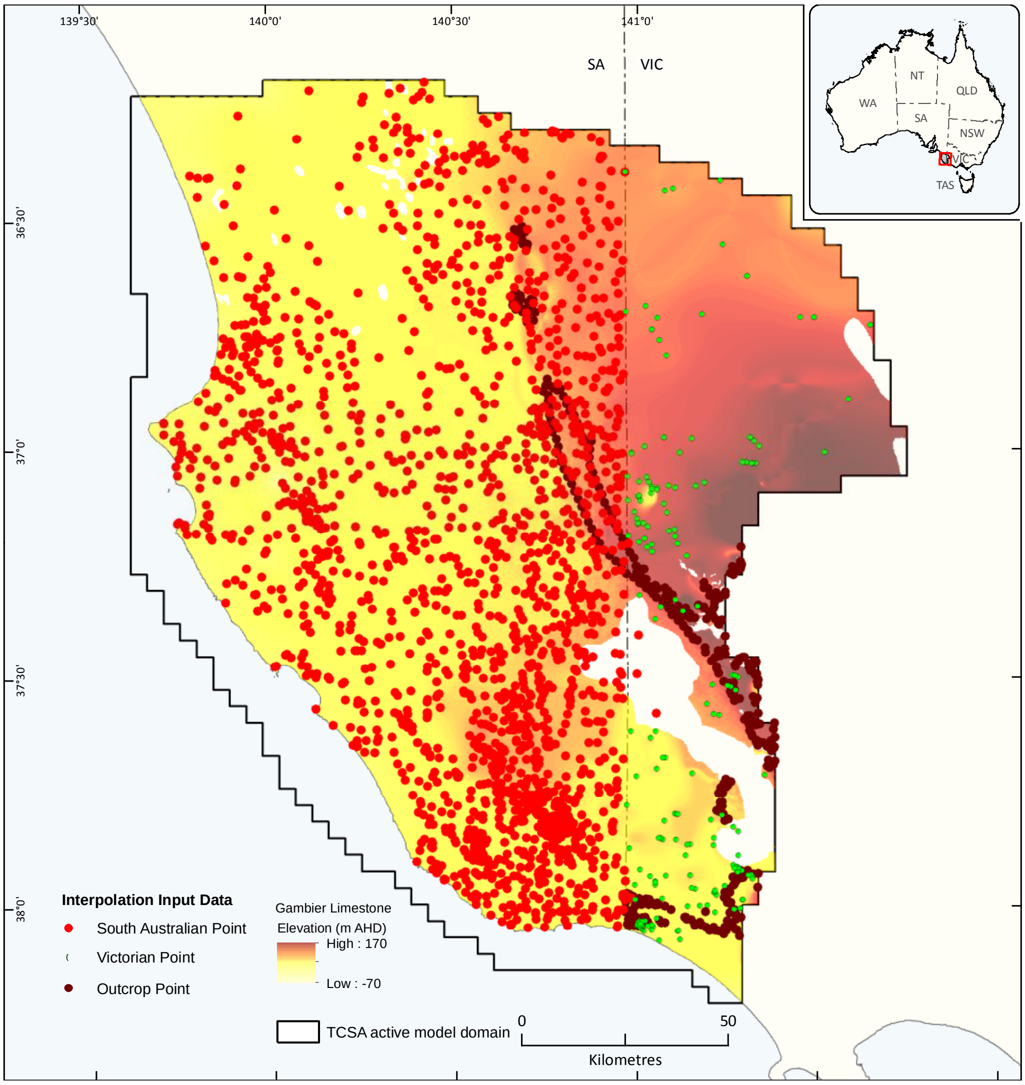


Figure A2. Top of unconfined Upper Tertiary Aquifer / Tertiary Limestone Aquifer. The data points used to derive the layer surface are also shown.

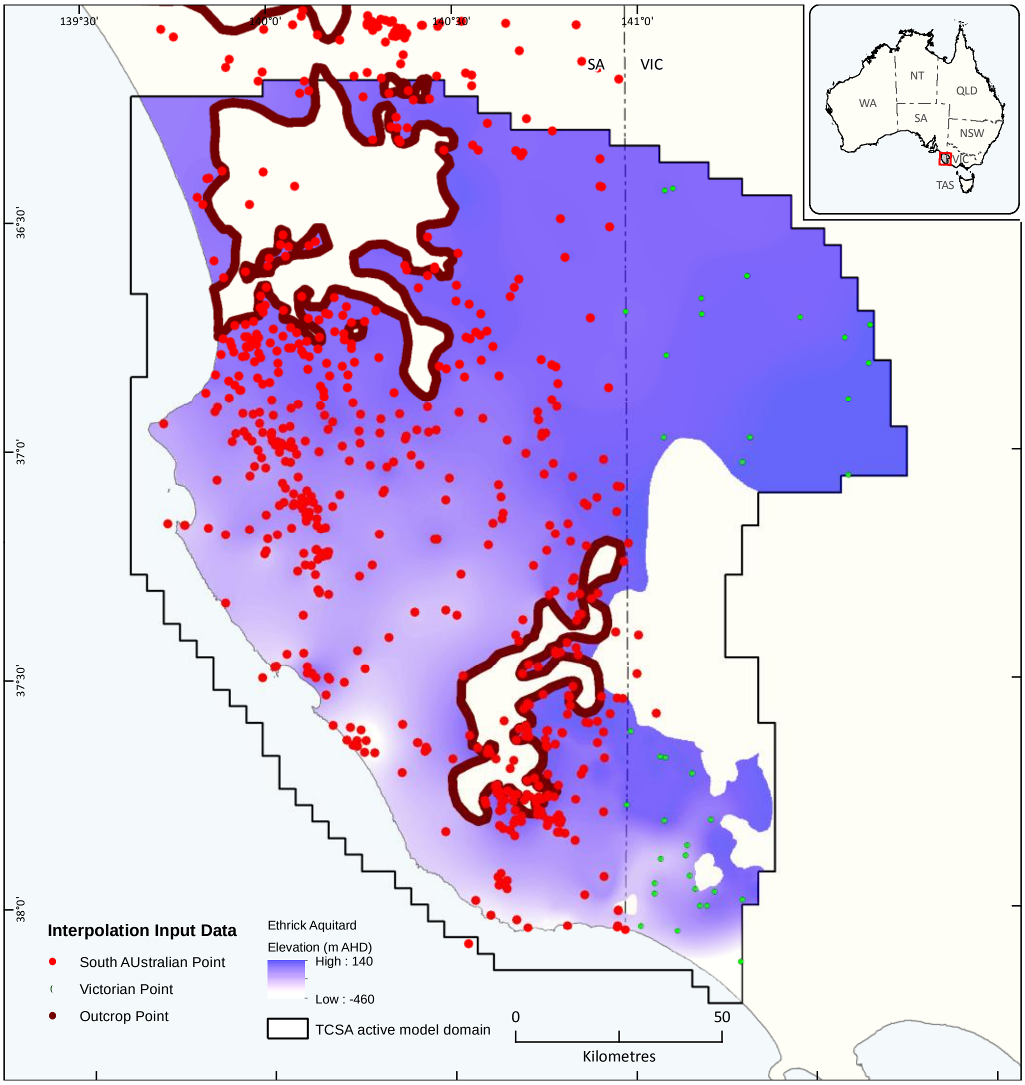


Figure A3. Top of Upper Tertiary Aquitard. The data points and interpreted absent areas used to derive the layer surface are also shown.

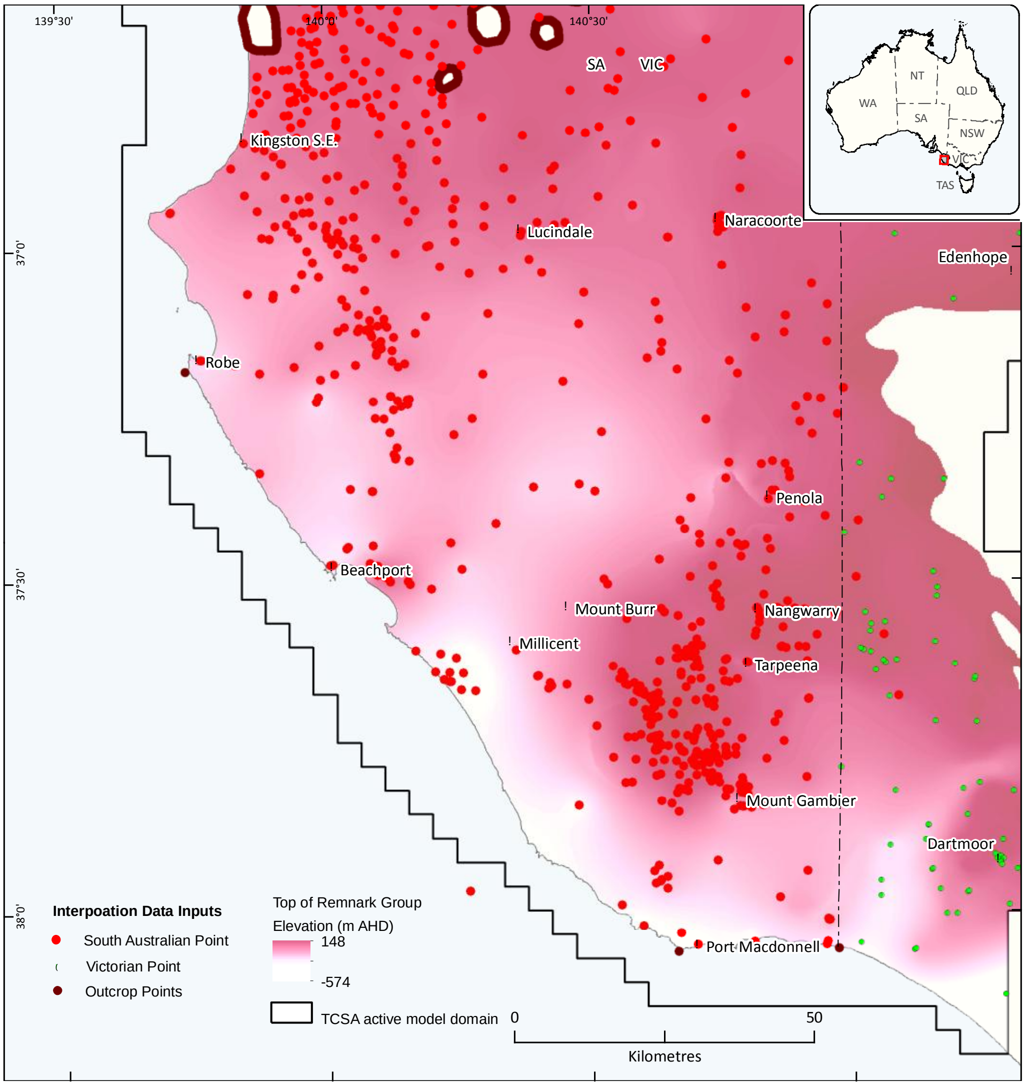


Figure A4. Top of Lower Tertiary Aquifer / Tertiary Confined Sand Aquifer (TCSA). The data points and absent areas used to derive the layer surface are also shown.

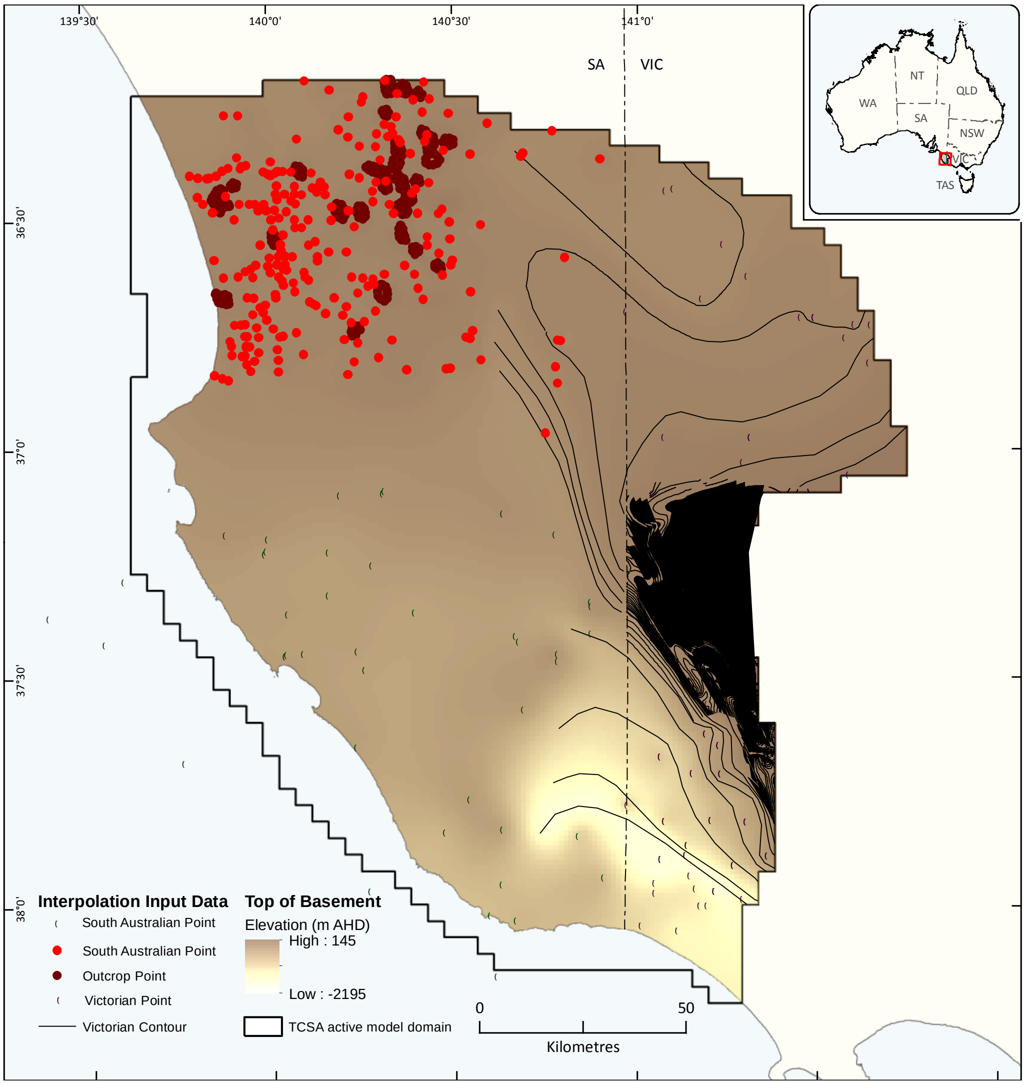


Figure A5. Top of Pre-Cainozoic sediments and basement. The data points and contours used to derive the layer surface are also shown.

Appendix B GIS technician's notes describing the methodology for refinement of the hydrostratigraphic model

DEM

For the purpose of importing into the model, the "dem_final_c" raster was not used as the basement outcrop areas had been removed. Instead, the "dem_stda_54" raster was used, which has a resolution of approximately 25 m x 25 m. The model cell nodes were exported as a shape file from Groundwater Vistas. Then the DEM values were extracted to the model cell nodes using the "Extract values to points" tool in ArcGIS. All the optional functions such as interpolation were turned off when executing this tool.

Gambier Limestone/Murray Group Limestone

The "Layer Builder Model" GIS tool developed from Phase 1 was used to reconstruct the raster surface. The tool was slightly modified to accommodate the additional input datasets from the South East Office (Jeff Lawson pers. comm. 2014).

Based on Steve Barnett pers. comm. (2014) and Jeff Lawson pers. comm. (2014), it was agreed that the gaps in the south-eastern part of the project area should be filled (the gaps were originally from the Victorian dataset).

The output was then resampled to 200 m x 200 m and reprojected from Lambert to MGA.

Finally, the output was corrected for negative thickness by using the GIS tool "Negative Thickness Correction" developed from Phase 1. Thickness was calculated as DEM – MGL and any cells with a negative thickness will be assigned a thickness of 3 m.

Ettrick Formation/Dilwyn Clay

The "Layer Builder Model" GIS tool developed from Phase 1 was used to reconstruct the raster surface. The tool was slightly modified to accommodate the additional input datasets from the South East Office (Jeff Lawson pers. comm. 2014). Additional data for the top of Dilwyn Clay was sourced from the NGIS database.

Based on Steve Barnett pers. comm. (2014) and Jeff Lawson pers. comm. (2014), it was agreed that the aquitard should be continuous across the project area, except where basement outcrops.

The "Topo to Raster" tool in ArcGIS was used.

The output was then corrected for negative thickness by using the GIS tool "Negative Thickness Correction" developed from Phase 1. Thickness was calculated as MGL – Aquitard and any cells with a negative thickness will be assigned a thickness of 3 m.

Finally, the basement outcrop areas in the north-western part of the project area were erased from the output using the "Extract by Mask" tool in ArcGIS.

Renmark Group/Dilwyn Sands

The discontinuous surface in the south-eastern part of the project area was fixed. No re-interpolation was undertaken for this layer. The negative thickness correction was applied to this surface again as there were changes in the overlying layers.

Basement

During Phase 1, additional data points from the South East Office were used instead of the contours from PIRSA. It was found that there was miscommunication on what the basement referred to (base of Dilwyn vs Top of Cretaceous).

During Phase 2, the contours from PIRSA were used instead of the data points from the South East Office. Also, some outlier contours (e.g. -3200 m AHD) were removed.

The “Layer Builder Model” GIS tool developed from Phase 1 was used to reconstruct the raster surface. The tool was slightly modified to accommodate the additional input datasets from the South East Office (Jeff Lawson pers. comm. 2014).

The output was then resampled to 200 m x 200 m and reprojected from Lambert to MGA.

Finally, the output was corrected for negative thickness by using the GIS tool “Negative Thickness Correction” developed from Phase 1. Thickness was calculated as Renmark Group – Basement and any cells with a negative thickness will be assigned a thickness of 3 m.

The Goyder Institute for Water Research is a partnership between the South Australian Government through the Department of Environment, Water and Natural Resources, CSIRO, Flinders University, the University of Adelaide and the University of South Australia.